Appendix B

The Eight Major Processes of the Nuclear Weapons Complex

Nuclear weapons production in the United States was a complex series of integrated manufacturing activities executed at multiple sites across the country. These activities have been grouped into eight major processes:

- *mining, milling, and refining* of uranium;
- *isotope separation* of uranium, lithium, boron and heavy water;
- *fuel and target fabrication* for production reactors;
- *reactor operations* to irradiate fuel and targets to produce nuclear materials;
- *chemical separations* of plutonium, uranium, and tritium from irradiated fuel and target elements;
- *component fabrication* of both nuclear and nonnuclear components;
- *weapon operations*, including assembly, maintenance, modification, and dismantlement of nuclear weapons; and
- *research, development, and testing*.[1]

Figure B-1 illustrates the major design elements of modern nuclear weapons in a generic manner, and explains how the weapons work. Figure B-2, "How Nuclear Weapons Are Made," illustrates the interrelationship among the eight processes.

Weapons complex configuration and weapons design and manufacturing processes in the U.S. have changed substantially from the Manhattan Project era. Laboratories and production plants developed better technologies to increase their capabilities, output, and efficiency. The weapons themselves have evolved considerably, becoming smaller, lighter, more powerful and versatile, safer, and more reliable. The federal government centralized the weapons complex in the early 1950s. By the mid-1960s, stockpiles of some key weapons materials became plentiful enough that the complex ceased producing them.

This appendix traces the evolution of each of the eight functional processes. It is important to note that the sites and processes changed over time as weapons designs, stockpile requirements, and technology evolved. Figure B-3 is comprised of four charts that illustrate the flow of materials through the nuclear weapons complex during four key stages in its history. Detailed discussions of the historical evolution of each of the eight nuclear weapons complex production processes are to be found in the sections following these charts.

In addition, this appendix examines the flow of nuclear and radioactive materials and suppliers of special materials, components and equipment. Due to the large scope of the nuclear weapons complex operation over the past fifty years, however, it is not possible to catalogue all the sites and contractors that contributed to it; nor is it possible to discuss every waste stream or release of contaminants.

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[1] *Nuclear weapons research, development, and testing take place concurrent with the other seven processes. Research and development are mostly complete before component fabrication begins, but testing may continue until a weapon system is retired from the stockpile.*

Figure B-1. Generic Design Elements of a Modern Nuclear Weapon
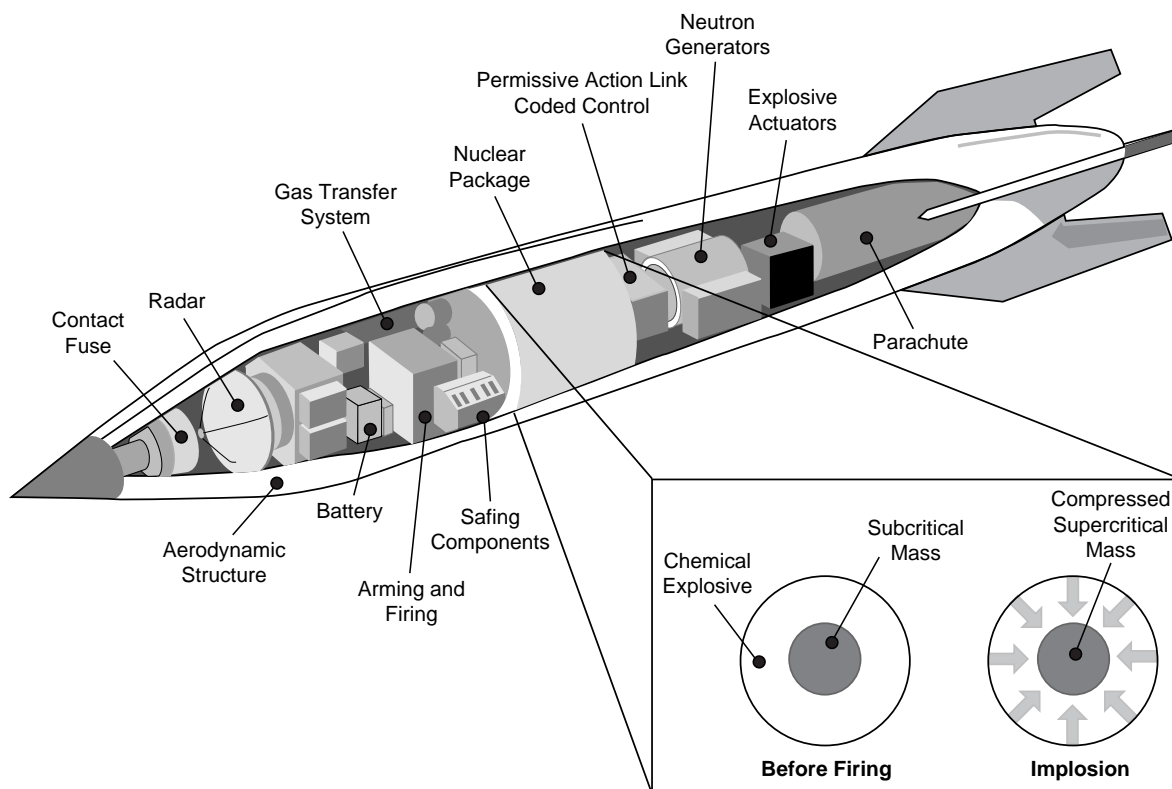
Nuclear explosions are produced by initiating and sustaining nuclear chain reactions in highly compressed material which can undergo both fission and fusion reactions. Modern strategic, and most tactical, nuclear weapons use a nuclear package with two assemblies: the primary assembly, which is used as the initial source of energy, and the secondary assembly, which provides additional explosive release. The primary assembly contains a central core, called the "pit," which is surrounded by a layer of high explosive. The "pit" is typically composed of plutonium-239 and/or highly enriched uranium (HEU), and other materials. HEU contains large fractions of the isotope uranium-235.

Primary Detonation	The primary nuclear explosion is initiated by detonating the layer of chemical high explosive that surrounds the "pit" which in turn drives the pit material into a compressed mass at the center of the primary assembly. Compression causes the fissile material to become supercritical. A neutron generator initiates a fission chain reaction in this supercritical mass. The implosion process is illustrated in the inset.
Boosting	In order to achieve higher explosive yields from primaries with relatively small quantities of pit material, a technique called "boosting" is used. Boosting is accomplished by injecting a mixture of tritium (T) and deuterium (D) gas into the pit. The implosion of the pit along with the onset of the fissioning process heats the D-T mixture to the point that the D-T atoms undergo fusion. The fusion reaction produces large quantities of very high-energy neutrons which flow through the compressed pit material and produce additional fission reactions.
Secondary Activation	Radiation from the explosion of the primary is contained and used to transfer energy to compress and ignite a physically seperate secondary component containing thermonuclear fuel. The secondary assembly is composed of lithium deuteride uranium and other materials. As the secondary implodes, the lithium, in the isotopic form lithium-6, is converted to tritium by neutron interactions, and the tritium product in turn undergoes fusion with the deuterium to create a thermonuclear explosion.
Nonnuclear Components	Nonnuclear components include contact fuses, radar components, aerodynamic structures, arming and firing systems, gas transfer systems, permissive action link coded controls, neutron generators, explosive actuators, safing components, batteries, and parachutes.

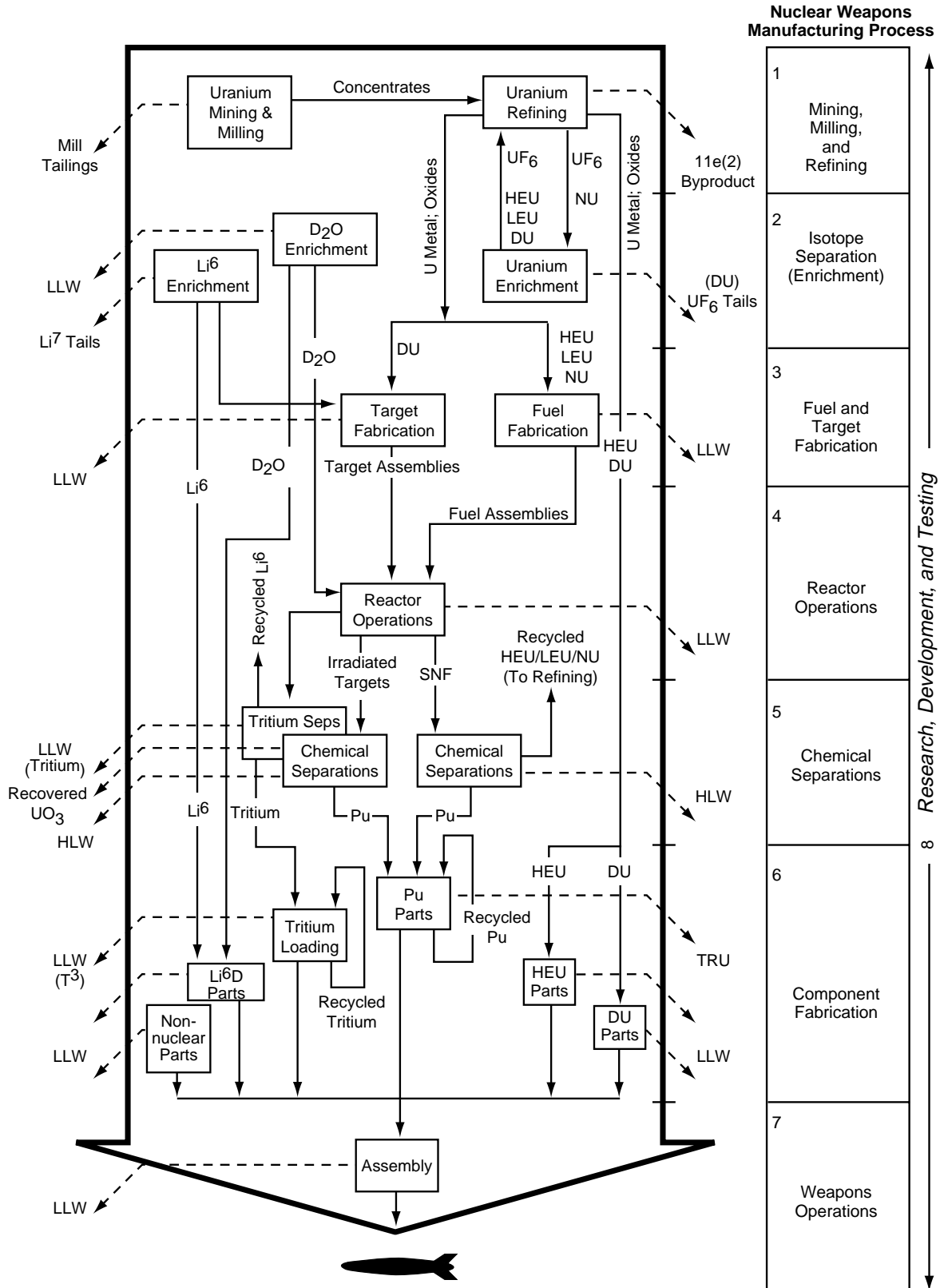**Figure B-2. How Nuclear Weapons are Made**

Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(one of four)*

The four following diagrams illustrate the flow of materials in the US nuclear weapons complex during the four major phases of its evolution.
They do not depict any single point in time. Some simplification was necessary to bring out the major features of each time period.
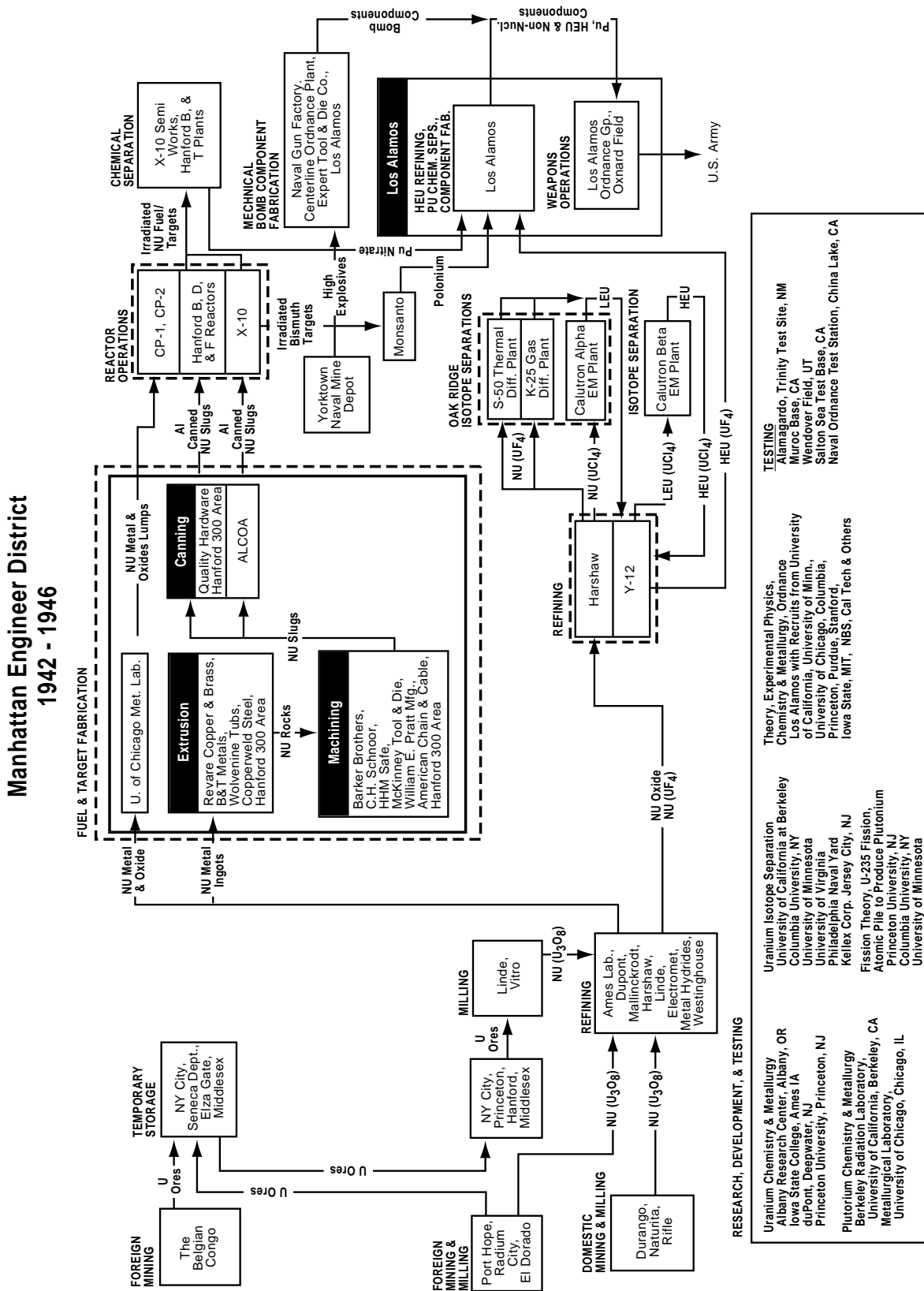
Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(two of four)*

121

Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(three of four)*

Figure B-3. Flow of Materials Through the Nuclear Weapons Complex   *(four of four)*

Atomic Energy Commission/Energy Research and Development Agency/Department of Energy
mid 1960s - late 1980s
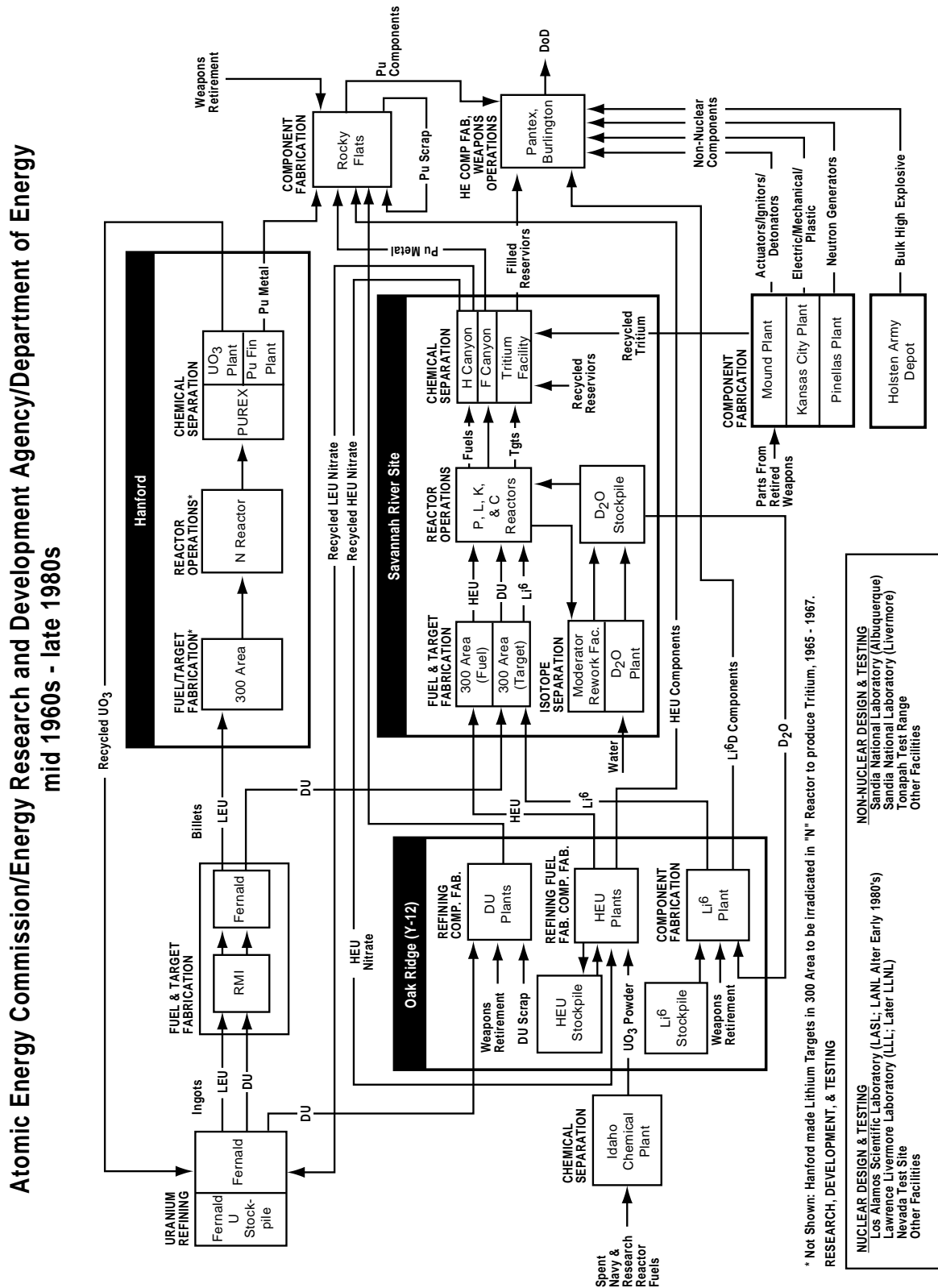
MINING, MILLING, AND REFINING URANIUM

Uranium *mining and milling* is the extraction of ore from the earth's crust and the physical and chemical processing of that ore to isolate uranium concentrate, also called uranium octaoxide, yellowcake, and U_3O_8. Mining and milling also includes ore assaying and sampling functions. High-grade "pitchblende" ores, in situ solution mining, and uranium recovery from phosphate and vanadium mining byproducts have also provided uranium for the U.S. nuclear weapons program.

Uranium *refining* consists of chemical processing to change uranium concentrate into feed material suitable for further processing, e.g., uranium hexafluoride (UF_6) for enrichment at the gaseous diffusion plants as well as uranium oxide or metal for fuel and target fabrication and weapons component manufacturing. In this report, refining includes the chemical conversions required for the reuse of uranium recovered from production scraps and irradiated nuclear fuels.
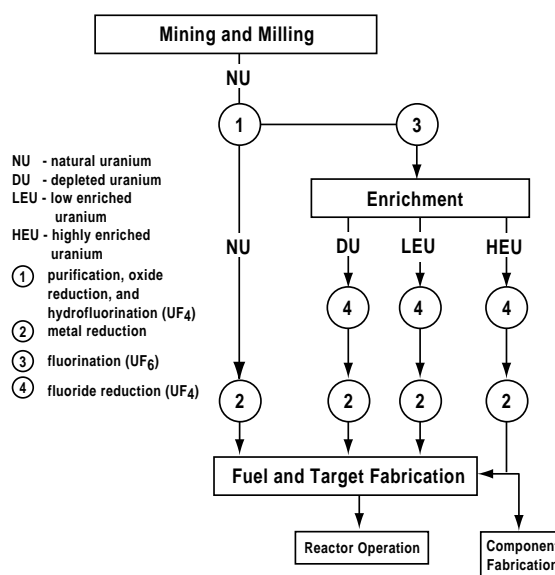
The refining steps and the wastes produced depended on the intended use of the product. Figure B-4 shows refining options commonly selected beginning in the early 1950s.

All of the U_3O_8 produced through the mining and milling process was natural uranium (NU) and was generally purified, reduced to an oxide, and hydrofluorinated to UF_4. Unenriched uranium that was to become reactor fuel was then reduced to metal (or converted to oxide) for further fabrication into reactor fuel elements. Uranium to be enriched was converted into UF_6 by fluorination. To be usable, the products of enrichment — highly-enriched uranium (HEU), low-enriched uranium (LEU), and depleted uranium (DU) — were converted from UF_6 back to UF_4, then reduced to metal for further fabrication into reactor targets (DU), fuel elements (LEU and HEU), and weapons parts (DU and HEU).

Manhattan Project Uranium Acquisitions

The initial purchases of uranium by the United States government took place

Figure B-4. Uranium Refining Processes

NU - natural uranium
DU - depleted uranium
LEU - low enriched uranium
HEU - highly enriched uranium
① purification, oxide reduction, and hydrofluorination (UF_4)
② metal reduction
③ fluorination (UF_6)
④ fluoride reduction (UF_4)

Uranium Refining

There were primarily two processes that emerged in the United States for refining U_3O_8 concentrate into other forms of uranium: the dry process and the wet process.

The dry process converted U_3O_8, through a series of steps, into uranium hexafluoride (UF_6) and then purified the UF_6 by fractional distillation. Wet process purification involved a chemical solvent extraction process to prepare a high-purity UO_3 compound from U_3O_8 concentrate; this material was further processed using the same chemical steps as the dry process. The wet process eventually became the procedure of choice because it produced purified uranium compounds earlier in the process, resulting in either high-purity UF_6 feed for the uranium enrichment plants or high-purity feed of other forms to be used as fuel and targets in production reactors.

Summary of the Wet Process:

• Purification and oxide reduction, which involved: (i) digestion (dissolution) and removal of uranium with nitric acid; (ii) solvent extraction using an organic solvent process followed by a stripping process for purification; (iii) denitration by thermal decomposition to UO_3, known as "orange oxide"; and (iv) reduction with hydrogen to UO_2, known as "brown oxide."

• Hydrofluorination by reacting UO_2 with anhydrous hydrogen fluoride gas (HF) to produce UF_4, known as "green salt."

• Either fluorination or reduction to metal, depending on the intended form of the end product. Fluorination converted UF_4 to UF_6 to be used as feed for the gaseous diffusion uranium-enrichment process. Alternatively, UF_4 was reduced to uranium metal to be used as fuel and targets in production reactors or directly as weapons components.
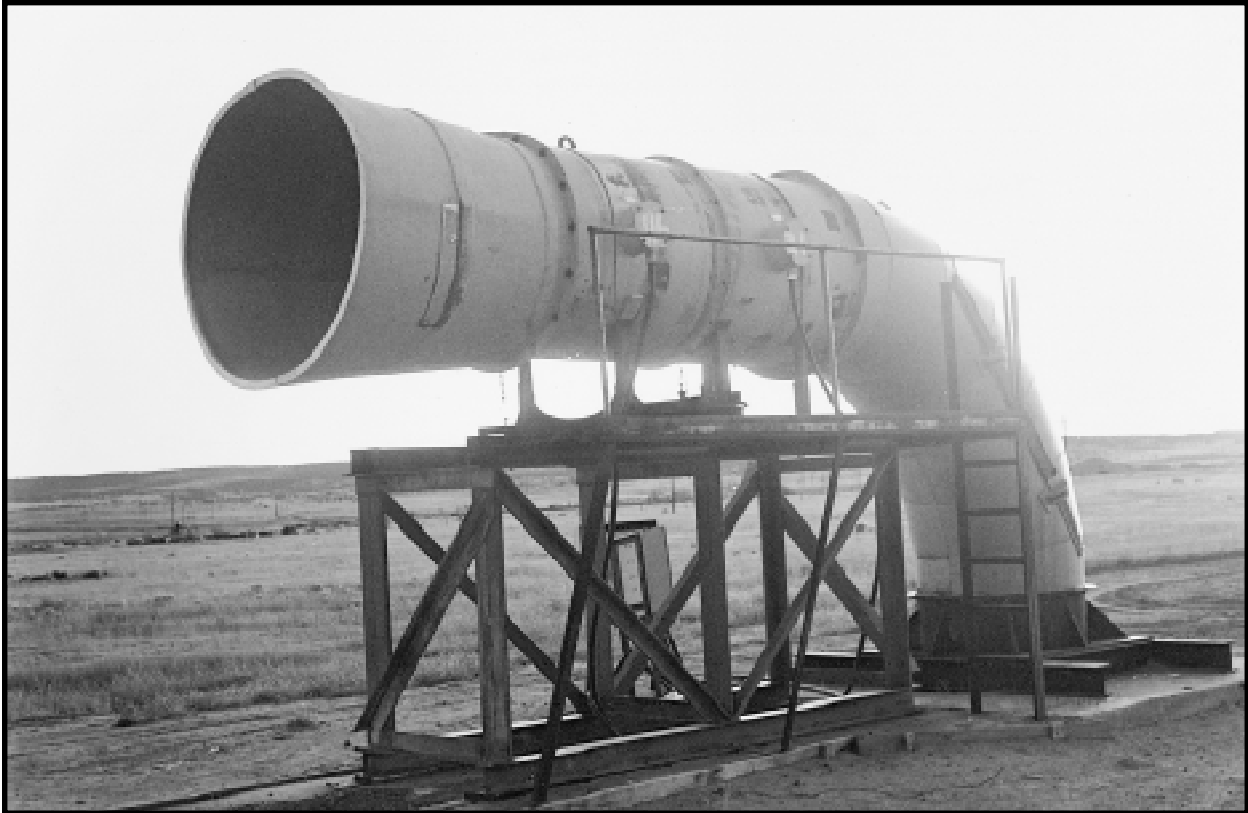
Radon gas vent. Radon is an odorless, colorless, radioactive gas, produced by uranium as it decays. It is a carcinogen. Vents like this one disperse radon gas from inside underground uranium mines, reducing miners' exposures. *Ambrosia Lake uranium mining district near Grants, New Mexico. August 18, 1982.*

The Jackpile open-pit uranium mine. This is one of the largest open-pit uranium mines in the United States. *Near Grants, New Mexico. August 19, 1982.*

The Durango uranium mill tailings pile on the banks of the Animas River is the mound on the left. Since this photograph was taken, these tailings have been stabilized. *Durango, Colorado. August 17, 1992.*

Industrial safety sign near a uranium mill in the Ambrosia Lake region. *Near Grants, New Mexico. August 19, 1982.*

between 1942 and 1944. The Manhattan Engineer District (MED) purchased uranium contained in pitchblende ores from the Belgian Congo (containing up to 65 percent uranium oxide by weight) from private radium suppliers. The suppliers retained ownership of the residues, which contained radium and other precious metals. Ores and U_3O_8 concentrate from the Great Bear Lake area of Canada (Radium City, Northwest Territories) and Port Hope, Ontario supplemented the African uranium. In addition, domestic uranium and vanadium mines and mills in Uravan, Durango, Grand Junction, and Naturita, Colorado; and Monticello, Utah on the Colorado Plateau supplied ores and lower grade concentrate.

The importation of these ores occurred at various locations. African ores entered the country primarily at ports along the northeast coast of the United States while the Canadian ores and concentrates moved primarily through ports along the great lakes in western New York and northern Ohio. Both the African ores and Canadian ores and concentrates were temporarily stored in New York City, at the Seneca Army Depot, in New York; in the Elza Gate area of Oak Ridge, Tennessee; or in Middlesex, New Jersey, prior to their transport to domestic milling and refining operations. Some of the concentrates received from Port Hope were temporarily stored in the Baker and Williams Warehouses on the west side of Manhattan in New York City.

Ore Sampling – The majority of the African ores were sampled and assayed at the Middlesex Sampling Plant in Middlesex, New Jersey established in 1943. Miscellaneous sampling activities were also conducted on site in the New York temporary storage areas, at Princeton University in New Jersey, and at the Hanford Site in Washington.

Manhattan Project Milling and Refining

Before the Manhattan Project began, the major use of uranium was as a coloring agent for ceramics. Developing the technology to produce pure uranium metal became a priority for the Manhattan Project. Universities and private companies with experience in related chemical processes participated in the task, and, as a result, Manhattan Project uranium refining was widespread.

During World War II, the African and Canadian ores were milled to black oxides, a form of U_3O_8 concentrate, by Linde in Tonawanda, New York, and at the Eldorado facilities in Port Hope, Ontario, Canada. Vitro, located in Canonsburg, Pennsylvania, chemically converted uranium ores to sodium diuranate. Mallinckrodt Chemical Works also produced black oxide at its Destrehan Street Plant in downtown St. Louis, Missouri.

Several sites refined black oxide and sodium diuranate to orange oxide (UO_3) and then to brown oxide (UO_2). Mallinckrodt produced about two thirds of the UO_2 while DuPont produced most of the remaining one third in its Deepwater, New Jersey plant–the Chambers Dye Works. Linde and Harshaw Chemical in Cleveland, Ohio also produced UO_2. In July 1942, Mallinckrodt began using ether to purify uranium in a solvent extraction process and DuPont followed suit. However, more than half of the DuPont product came from uranium peroxide obtained by processing uranium-bearing scrap. UO_3 and UO_2 were, in turn, refined into green salt (UF_4) by DuPont, Harshaw, Mallinckrodt, and Linde. Mallinckrodt was the major producer.

Several organizations developed processes to produce pure uranium metal. Westinghouse Electric in Bloomfield, New Jersey; Metal Hydrides in Beverly, Massachusetts; and Iowa State College in Ames, Iowa, produced the uranium metal used in the Stagg Field reactor. Westinghouse used a photochemical process while Metal Hydrides and Iowa State employed a calcium reduction process starting with UF_4. Metal Hydrides and Westinghouse continued uranium metal production through the summer of 1943. However, the Metal Hydrides product was impure and pyrophoric, and the throughput of the Westinghouse process was insufficient to meet the project's needs.

Researchers at Iowa State soon perfected a magnesium reduction process (also investigated by Brush Beryllium Co. of Cleveland, Ohio) which quickly became the standard. Electro Metallurgical Company in Niagra Falls, New York, also known as "Electromet," built the largest metal reduction plant.

The Port Hope uranium refinery in Ontario, Canada, refined uranium for the Manhattan Project, and for the next 20 years it refined uranium for the U.S. nuclear weapons program. *Eldorado Uranium Refinery, Blind River, Ontario, Canada. August 25, 1986.*

Mallinckrodt in St. Louis, Missouri; DuPont in Deepwater, New Jersey; and Iowa State University also produced uranium metal using the magnesium process. Metal Hydrides, DuPont, and Iowa State recycled scarce uranium scrap. Quality control was provided by the University of Chicago Metallurgical Laboratory (the "MetLab"), Princeton University, the Massachusetts Institute of Technology, and the National Bureau of Standards in Washington, D.C.

Beginning in 1944, the Oak Ridge Y-12 Plant converted UO_3 to uranium tetrachloride (UCl_4) feed for the Calutron electromagnetic spectrograph. Harshaw and DuPont produced hexafluoride (UF_6) from UF_4 as feed for the S-50 Thermal Diffusion and K-25 Gaseous Diffusion projects in Oak Ridge. By early 1945, the S-50 and K-25 plants were supplying low-enriched UF_6, which was also converted to UCl_4 at Y-12 to be further enriched in Calutrons.

In 1945, the HEU (also called "Oralloy," for <u>O</u>ak <u>R</u>idge <u>Alloy</u>) from the Calutrons was converted at Y-12 into UF_4 and sent to Los Alamos. The Los Alamos Chemistry and Metallurgy Division further purified the HEU and reduced it to metal for the "Little Boy" atomic bomb. Refining highly enriched uranium (HEU) required special considerations because of criticality and security concerns.

Post-War Uranium Purchases

After the War, the United States continued to import uranium from Canada and the Belgian Congo. Australia, South Africa, Portugal, and other nations also exported uranium to the United States. The Atomic Energy Commission (AEC) began a program to stimulate the domestic mining and milling of uranium in 1948; as a result, the domestic uranium mining and milling industry grew rapidly. Hundreds of uranium mines in New Mexico, Colorado, Arizona, Utah, Oregon, Texas, Wyoming, and Washington

Soil contaminated with uranium residues at the Middlesex Sampling Plant. From 1943 until 1955, most of the uranium purchased by AEC was assayed and sampled at Middlesex. These uranium residues continuously release radon gas. To contain the gas, the soil is covered with an impermeable barrier. *Middlesex Sampling Plant, Middlesex, New Jersey. December 10, 1993.*

produced uranium ore which was also milled at plants in those and other states.[2] Phosphate mining plants in Florida, Louisiana, and Texas produced uranium as a byproduct, while two plants in the Dakotas extracted uranium from lignite coal ashes.

All ore sampling activities were centralized at Middlesex in the mid-1940s. The Middlesex Sampling Plant discontinued its sampling activities in 1955. The ore sampling function was transferred to the Feed Materials Production Center in Fernald, Ohio. After the Weldon Spring Plant was constructed in 1957, domestic uranium concentrates were shipped there for sampling as well.

Until March of 1962, when AEC's Domestic Uranium Program and ore purchases for weapons programs terminated, AEC purchased and held uranium ore and then gradually sold it back to the mills as their capacity increased. In total, MED and AEC purchased over 3.6 million tons of domestic uranium ore, equivalent to 11,373 tons of U_3O_8 concentrate. AEC's Grand Junction, Colorado office managed the ore purchasing program. By the end of 1966, AEC had no unprocessed ore remaining in storage. AEC domestic and foreign concentrate purchases continued until 1971 and totaled 325,000 tons, consisting of 175,000 tons from domestic sources and 150,000 tons from foreign sources.

Besides uranium, AEC also purchased thorium, another naturally occurring radioactive source material. The Middlesex Sampling Plant was used primarily for sampling and storage of thorium materials and residues from 1955 until September 1967. Maywood Chemical Works (Maywood, New Jersey), Rare Earths, Inc. (Wayne, New Jersey), and W.R. Grace (Curtis Bay, Maryland) milled thorium for AEC.

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[2] *A total of 24 uranium processing sites that sold ore to AEC and thousands of "vicinity properties" where uranium mill tailings were used as landfill or construction material are presently being remediated under the Uranium Mill Tailings Remedial Action project (UMTRA). UMTRA was established by Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. Uranium and thorium mills licensed to operate as of January 1, 1978 are remediated under Title II of UMTRCA. DOE reimburses the mill owners for a portion of the costs of this work based on the amount of concentrates purchased from the mill by the Department and its predecessors.*
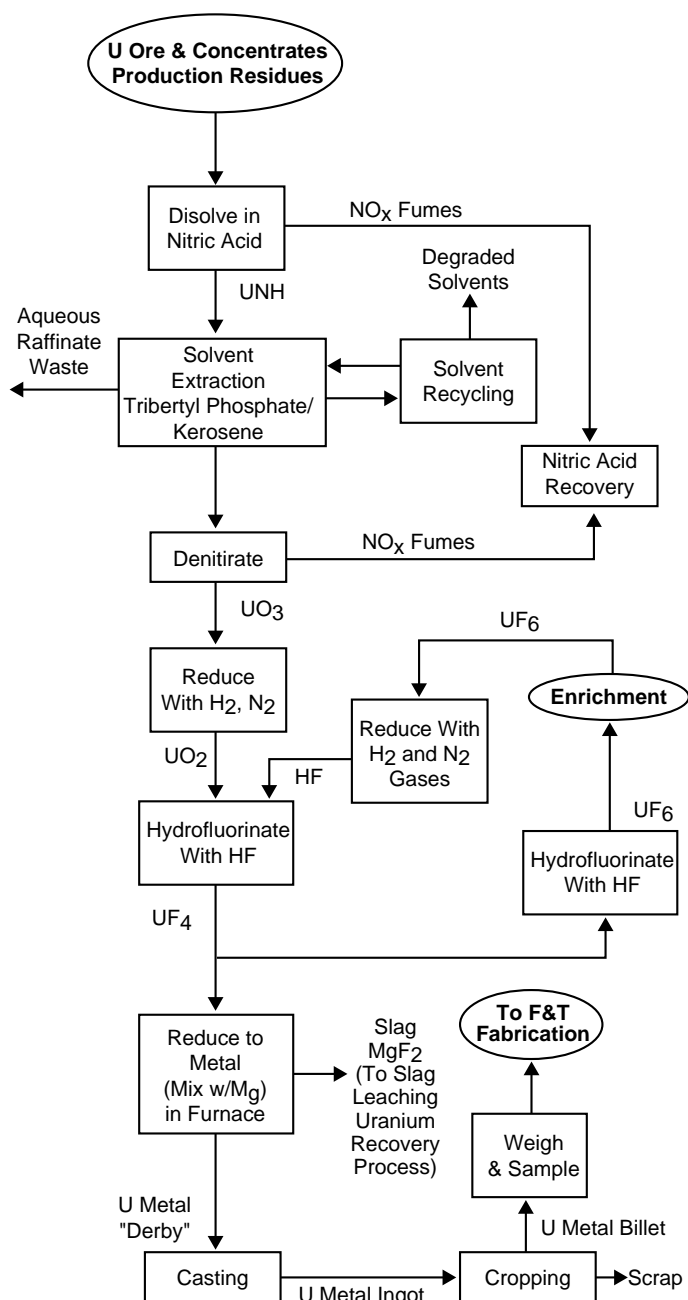
Post-War Uranium Refining

After the war ended, Mallinckrodt Chemical Works continued to convert U_3O_8 to UO_3 and UO_2 in a new plant on Destrehan Street in St. Louis. Harshaw Chemical Company also produced UO_2 until 1951. Electromet produced UF_4 that was reduced to metallic uranium either on site in Niagra Falls, New York or by Mallinckrodt in St. Louis, Missouri. Electromet continued to produce UF_4 and uranium metal until 1949. Harshaw and Mallinckrodt produced green salt (UF_4) as well, shutting down in 1951 and 1957 respectively.

In the early 1950s, AEC built two new feed materials plants, the Weldon Spring Plant in St. Charles County, Missouri and the Fernald Plant near Cincinnati, Ohio to expand and centralize AEC's uranium refining functions. Fernald and Weldon Spring assumes almost all of the functions previously carried out by Mallinckrodt, Harshaw and Electronet. Weldon Spring produced UO_3 and UO_2 from 1956 to 1966, and Fernald from 1952 through 1962, when the site's uranium refinery was placed on standby. The Fernald refinery was reactivated with the shutdown of the Weldon Spring plant in 1966. Government purchases of uranium concentrate ended in 1971. Refining of recycled uranium at Fernald continued until the plant was closed in July 1989. Fernald also processed thorium periodically between 1954 and 1975, albeit in smaller amounts than uranium.

Harshaw Chemical continued to produce most of the UF_6 feed for the K-25 uranium enrichment plant at its Cleveland, Ohio plant after the war. However, in December 1947, the F2 Plant at K-25 became operational, allowing the plant to produce its own feed by initially converting UO_3 to UO_2 to UF_4 to UF_6 and later UO_2 to UF_6. Harshaw expanded its UF_6 production in 1947, and was placed on standby by May 1953. When the Paducah and Portsmouth Gaseous Diffusion Plants were built and started up in 1954 and 1956, they included feed operations similar to that at K-25. The Oak Ridge, Portsmouth and Paducah feed plants were shut down in 1962, and the conversion of U_3O_8 to UF_6 for gaseous diffusion plant feed was taken over by the privately-owned Allied Chemical Co. Plant in Metropolis, Illinois. Thereafter, UF_6 feed came from commercial sources, existing stocks, and partially-depleted UF_6 tails stored at the enrichment plants.

Natural, low-enriched and depleted uranium were reduced to metal at the Weldon Spring and Fernald plants after the early 1950s. These plants also recycled uranium from scraps and residues such as slag, machining chips, and cleaning solvents. Highly-enriched uranium processing has been centralized at the

Figure B-5. Uranium Refining (Fernald)

```
              ( U Ore & Concentrates
                Production Residues )
                        |
                        v
              +-------------------+      NOx Fumes
              | Disolve in        |---------------------->
              | Nitric Acid       |          Degraded
              +-------------------+          Solvents
                        | UNH                    ^
                        v                        |
  Aqueous   +-------------------+      +-----------------+
  Raffinate<| Solvent           |----->| Solvent         |
  Waste     | Extraction        |<-----| Recycling       |
            | Tribertyl Phosphate/     +-----------------+
            | Kerosene          |
            +-------------------+          +-----------------+
                        |                  | Nitric Acid     |
                        v                  | Recovery        |
              +-------------------+        +-----------------+
              | Denitirate        |  NOx Fumes   ^
              +-------------------+-------------->|
                        | UO3
                        v                             UF6
              +-------------------+         +------------------+
              | Reduce            |         | Reduce With      |
              | With H2, N2       |         | H2 and N2        |   ( Enrichment )
              +-------------------+    HF   | Gases            |
                        | UO2  <-----------+------------------+
                        v                            UF6
              +-------------------+         +------------------+
              | Hydrofluorinate   |         | Hydrofluorinate  |
              | With HF           |         | With HF          |
              +-------------------+         +------------------+
                        | UF4                      ^
                        +--------------------------+
                        v
              +-------------------+    Slag        ( To F&T
              | Reduce to         |    MgF2          Fabrication )
              | Metal             |--> (To Slag         ^
              | (Mix w/Mg)        |    Leaching         |
              | in Furnace        |    Uranium    +-----------+
              +-------------------+    Recovery    | Weigh     |
                        |              Process)    | & Sample  |
              U Metal                              +-----------+
              "Derby"                                   ^ U Metal Billet
                        v                               |
              +-----------+  U Metal Ingot  +-----------+
              | Casting   |---------------->| Cropping  |---> Scrap
              +-----------+                 +-----------+
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Vitro Properties. Uranium ore for the Manhattan Project was milled at this site. Today, the site is part of the Uranium Mill Tailings Remedial Action project. *Canonsburg, Pennsylvania. June 13, 1984.*

Inside Building 51 of the Mallinckrodt Chemical Works, 40 tons of purified uranium were produced for Fermi's Chicago pile. This site processed uranium for AEC until 1957. *Downtown St. Louis FUSRAP Site, Missouri. January 29, 1994.*

St. Louis Airport Storage Site (SLAPSS). In 1946, the Manhattan Engineer District condemned 22 acres of farmland to store uranium-, radium-, and thorium-contaminated wastes generated at the downtown St. Louis uranium refinery. Because of contamination, this site is now part of the Formerly Utilized Sites Remedial Action Program. The man in the photo is measuring radiation levels outside the site fence line. *St. Louis Airport Storage Site, St. Louis, Missouri. January 30, 1994.*

Weldon Spring Raffinate Pit 4. The Weldon Spring Plant processed uranium for AEC from 1957 until 1966. Four lagoons, called "raffinate pits," and a nearby quarry received uranium-redium-, and thorium-contained residues and wastes from the plant's uranium refinery and reactor fuel factory. Contaminated rubble and soil from the demolition of a uranium processing facility in downtown St. Louis and debris from the adjacent Army munitions factory and chemical plant have also been dumped here. DOE plans to remove sludge from the pits, treat it, and entomb it onsite by September, 2001. *Raffinate Pit 4, Weldon Spring Plant, St. Charles County, Missouri. January 29, 1994.*

Oak Ridge Y-12 Plant since 1947, when the Y-12 plant took over from Los Alamos the mission of reducing highly-enriched UF_6 to metal. The Y-12 metal reduction plant shut down in 1964 when sufficient HEU reserves for weapons had accumulated and the gaseous diffusion plants stopped producing HEU for weapons. Y-12 also purified and recycled HEU from production scraps and residues and returned weapon parts. This mission is still carried out at the Y-12 Plant at the present time.

Environmental Legacies of Uranium Mining, Milling, and Refining

The residues from refining the African ores which contain a considerable amount of radium and other valuable materials, were initially stored at the Lake Ontario Ordnance Works in Lewiston, New York. The ore supplier, African Metals Corporation, retained ownership of the radium and precious metal content of these residues until 1983. Some of the residues were moved to the K-65 silos at the Feed Materials Production Center in Fernald, Ohio in the early 1950s. Additional residues from refining at Fernald and the Mallinckrodt Chemical Works in St. Louis were stored in the same silos. African Metals exported a portion of the residues to their facility in Belgium.

Off site disposal of uranium refining residues from the early MED and AEC refining operations took place near St. Louis, Missouri; at Lewiston and Tonawanda, New York; and Canonsburg, Pennsylvania. Residues from the Mallinckrodt Chemical Works operations were deposited at the current St. Louis Airport Site. In 1967, a private firm purchased these residues and stored and processed them at what is now known as the Latty Avenue Properties.

The former Haist property, now known as Ashland Oil #1 (Tonawanda) was used to store residual material from the Linde refining operations. Some of these residues were later moved to the adjacent Ashland Oil #2 and Seaway Landfill. Vitro deposited wastes from its Canonsburg works at the Pennsylvania Railroad Landfill Site (Burrell Township, Pennsylvania). Uranium- and radium-contaminated building rubble from the demolition of the Mallinckrodt uranium ore processing facility in St. Louis was disposed of at the Weldon Spring Quarry and Raffinate Pits. The Middlesex Municipal Landfill in New Jersey received construction debris from the Middlesex Sampling Plant.

Fernald – The Fernald plant produced approximately 2.2 pounds of waste for each of the 400 million pounds of uranium metal it processed. Solid hazardous and low-level wastes were disposed on site in a series of six waste pits, the Burn Pit, and the "Clearwell." Two fly ash piles on site also received construction rubble and ash from electrostatic precipitators used to control uranium dust emissions. See Table B-1 for a description of the waste pits at Fernald. Waste Pit 3 is known to have leaked into the aquifer underlying the site. Laboratory chemicals and low-level combustible materials were disposed of in the Burn Pit beginning in 1957. The Clearwell received surface runoff from the waste pit area and, until 1987, was used as a final settling basin before runoff was discharged to the Great Miami River. After 1987, the Clearwell received only decanted water from Waste Pit 5, some of which was pumped there from Waste Pit 6. Waste Pits 2, 4, and 6 have the highest levels of uranium-238 while Pits 3 and 5 contain higher levels of thoriam-230 and mercury. The Clearwell and Pit 5 contain the highest concentrations of radium-226. The pits also contain elevated levels of aluminum, calcium, iron, magnesium, and PCBs. The Burn Pit has been found to contain high levels of silver and lead. Uranium, thorium, organic chemicals, and PCBs have migrated from the waste pits into the surrounding environment.

Fernald treated liquid effluents and discharged them to the Great Miami River and Paddy's Run, a stream running along the plant boundary. Processing wastes from Plant 1 (the Sampling Plant, which also reconditioned steel drums used to store and transport uranium salts, oxides and residues) containing mixed wastes including uranium, thorium, barium salts, and waste oils contaminated with lead were stored on a concrete pad in drums beginning in 1952. By July 1990, 45,000 drums had accumulated. DOE shipped these wastes to the Nevada Test Site for disposal beginning in 1985.

The Feed Materials Production Center processed uranium "feed" for the U.S. nuclear weapons complex from 1951 until 1989. Its main tasks were refining uranium and manufacturing reactor fuel and targets. Today, the site no longer produces uranium feed materials. It has been renamed the "Fernald Environmental Management Project." *Fernald, 20 miles outside Cincinnati, Ohio. May 22, 1984.*

Table B-1. Description of the Waste Pits at the FMPC (Fernald, OH)

Waste Pit	Date opened	Date closed	Volume of waste	Description of waste
Pit 1	1952	1959	33,672 cubic yards	Solid LLW; 52,000 kg U
Pit 2	1957	1964	18,478 cubic yards	Solid LLW; 1.2 million kg U, 400 kg Th
Pit 3	1959	1977	237,053 cubic yards	Primarily concentrated, lime-neutralized radioactive nitrate raffinates; 129,000kg U, 400 kg Th
Pit 4	1960	1986	60,000 cubic yards	Concentrated, lime-neutralized radioactive nitrate raffinates; LLW containing barium chloride, 5/81-4/83; 3 million kg U, 61,800 kg Th
Pit 5	1968	1987	98,841 cubic yards	Liquid waste slurries from the refinery and recovery plant until 1983; clear decant, filtrate and nonradioactive slurries
Pit 6	1979	1987	11,556 cubic yards	Fine-grained wastes, including green salt (UF_4), filter cakes and process residues; 845,000 kg U

Weldon Spring – The Weldon Spring Plant used a nearby quarry and four waste lagoons (called " Raffinate Pits") to store contaminated residue from uranium processing. Workers disposed of contaminated rubble from the demolition of the downtown St. Louis uranium processing plant in these pits as well. The quarry was also used to dispose of contaminated wastes from the plant and from the Army ordnance plant formerly located at the site. Wastes and contaminated soils from Weldon Spring are being consolidated into a disposal cell on the former site of the chemical plant.

The K-65 Silo. This underground silo at Fernald contains residues from African pitchblende ore refined in upstate New York for the Manhattan Project. The Fernald Plant also placed in this silo wastes from its own uranium processing. Radon gas from this silo and another adjacent to it was the major source of radiation exposure to people in the surrounding area. *K-65 Silo, Fernald Environmental Management Project, Ohio. January 29, 1994.*

ISOTOPE SEPARATION

Isotope Separation, also commonly known as "enrichment," is the process of concentrating one or more isotopes of the same element. Three elements that have been isotopically separated in large quantities in the U.S. nuclear weapons complex are uranium, lithium, and hydrogen. Smaller amounts of various other materials, including boron, have also been isotopically enriched for use in the nuclear weapons programs.

Uranium – Uranium enrichment begins with natural uranium (NU) and results in enriched uranium (EU) and depleted uranium (DU). NU contains 0.711 percent of the isotope uranium-235, the remainder being almost entirely uranium-238. EU is uranium that has been processed so that it contains more than a 0.711 percent concentration of uranium-235. DU contains less than 0.711 percent uranium-235. EU and NU are made into reactor fuel elements which sustain the chain reaction while absorbing neutrons to produce plutonium-239. DU is used in weapon components and in reactor targets to be irradiated for the production of plutonium-239. Highly enriched uranium (HEU) contains more that 20 percent of the uranium-235 isotope. HEU is used in weapons components and is also used as a reactor fuel, depending on the enrichment level.

Lithium – Natural lithium consists of 7.5 percent lithium 6 and 92.5 percent lithium-7. Lithium enriched in the lighter lithium-6 isotope is irradiated in reactors to produce tritium, which is used in nuclear weapons. Some weapons components are made from Li-6 which has been chemically combined with deuterium to form a ceramic material, lithium deuteride.

Hydrogen – Naturally occurring hydrogen contains 0.015 percent of the deuterium isotope (H^2 or D). "Heavy water" is produced by enriching water in deuterium. The resulting liquid, D_2O, is used as a coolant and moderator for some of the Department's nuclear materials production reactors. Deuterium separated from heavy water is also used in components of nuclear weapons.

Boron – Boron-10 was produced for the weapons complex because it is a powerful neutron absorber used to control neutron fluxes in reactors and nuclear weapons.
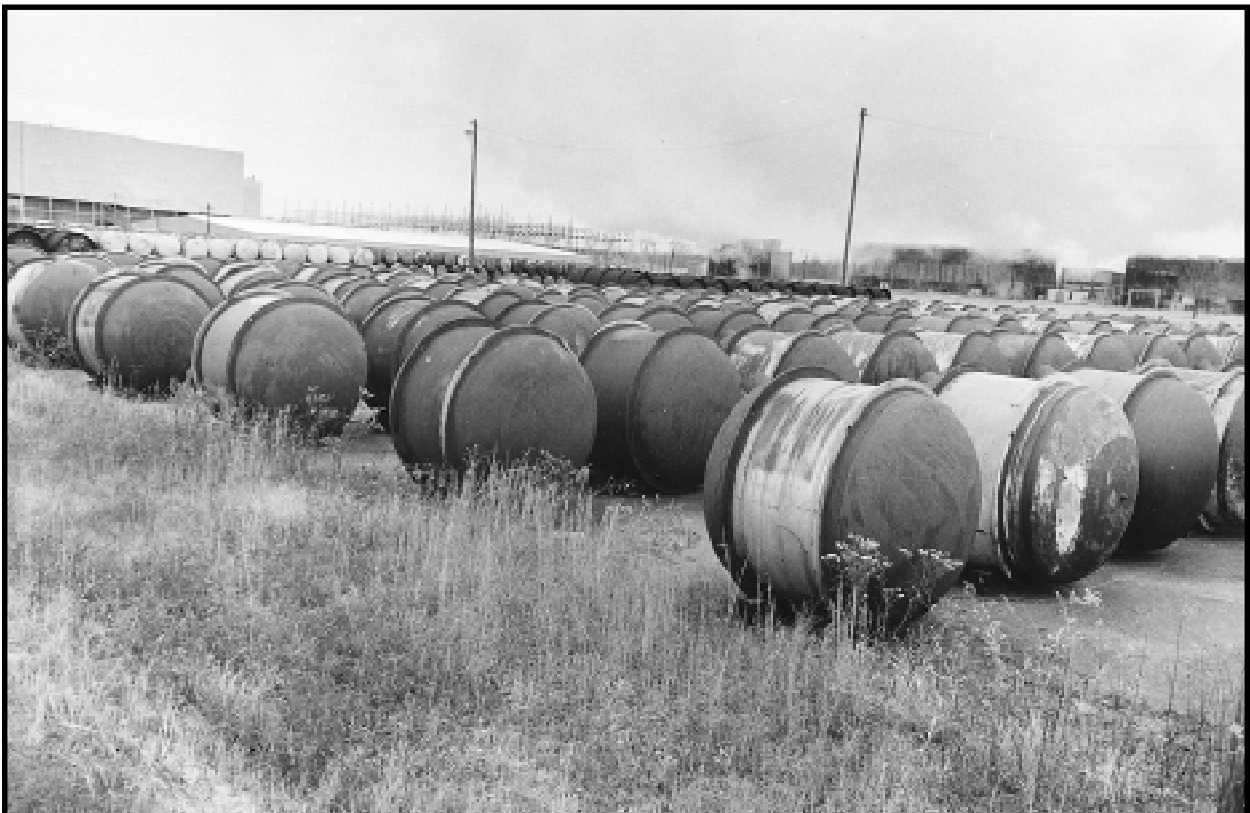
Uranium Enrichment

Uranium Enrichment in the Manhattan Project, – The Manhattan Project simultaneously pursued plutonium and highly enriched uranium as fissile materials for atomic weapons. Thus, one of the key challenges in the initial development of the nuclear weapons program was separating the isotopes of uranium. Because uranium isotopes have almost identical chemical properties, they cannot be separated using chemical processes. Uranium-235 and uranium-238 must be separated physically, by exploiting the small difference in the atomic masses of the two isotopes. Because of the small difference in the weights of the two isotopes, even physical separation is difficult. Uranium's complex chemistry and the corrosive and reactive nature of some of the important uranium compounds complicate handling of large quantities of uranium.

The pre-war Office of Scientific Research and Development and MED initially investigated four processes for the isotopic enrichment of uranium: gas centrifuge, thermal diffusion, electromagnetic spectrograph, and gaseous diffusion. MED developed these four processes through the pilot plant stage. An explanation of each process is provided in the text box "Uranium Enrichment Processes."

The electromagnetic, thermal diffusion, and gaseous diffusion processes all contributed to the production of enriched uranium during the Manhattan project. Technical difficulties prevented the successful use of gas centrifuge during World War II. Two stages of electromagnetic "Calutrons" at the Y-12 Plant (grouped into "racetracks," named for their oval shape) produced all of the HEU for "Little Boy," the atomic bomb detonated over Hiroshima, Japan. Y-12 featured nine first-stage "alpha" racetracks and four second-stage "beta" racetracks.

Portsmouth Gaseous Diffusion Plant. Built between 1952 and 1956 during AEC's expansion of its uranium enrichment capacity, the Portsmouth plant enriched uranium up to 97 percent uranium-235. The facility is currently operated by the United States Enrichment Corporation under a lease from DOE; it now enriches uranium for commercial reactor fuel. *Portsmouth Gaseous Diffusion Plant, Piketon, Ohio. June 20, 1982.*

Gaseous diffusion "tails." These cylinders contain depleted uranium hexofluoride left over from the uranium enrichment process. They are stored on the grounds of the Paducah, Kentucky uranium enrichment plant. *Paducah Gaseous Diffusion Plant, Kentucky. December 18, 1985.*

Figure B-6. Processes for Enriching Uranium

Gas Centrifuge

Thermal Diffusion

Electromagnetic

Gaseous Diffusion
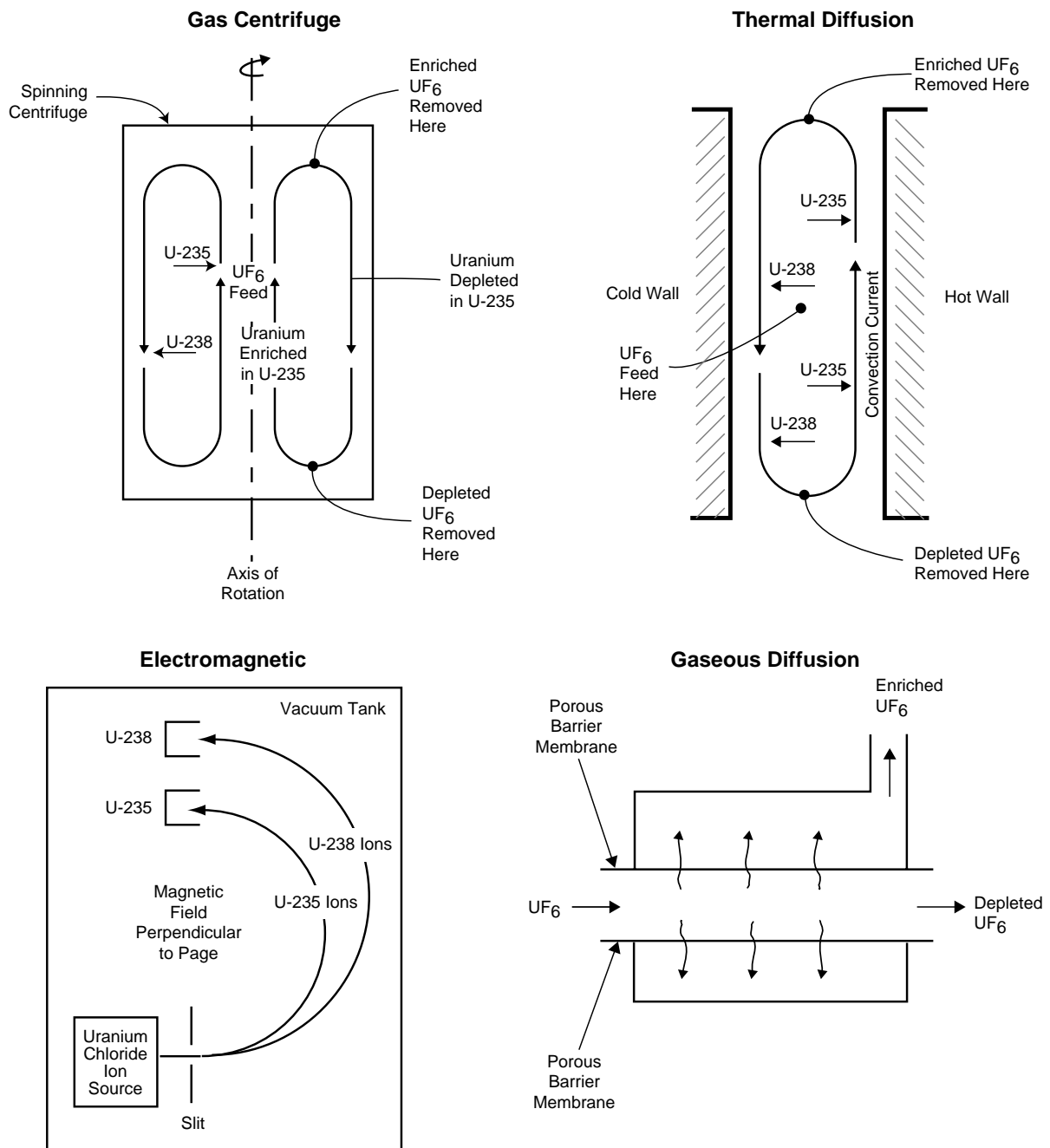
The Y-12 plant calutrons were created by various firms located in many different regions of the country. Tennessee Eastman coordinated the construction and procurement effort and Stone & Webster of Boston, Massachusetts designed the Y-12 Plant. Westinghouse Electric produced vacuum tanks, liners, ion sources, and collectors in their Pittsburgh factories. General Electric of Schenectady, New York supplied the high-voltage electrical equipment. Allis-Chalmers, located in Milwaukee, Wisconsin made vacuum pumps, and the Chapman Valve Company of Indian Orchard, Massachusetts manufactured vacuum valves. Due to wartime copper shortages, the magnetic coils for the calutrons were wound with silver borrowed from the U.S. Treasury depository in West Point, New York. It was cast into billets by the

Defense Plant Corporation in Carteret, New Jersey, extruded and rolled into strips by Phelps Dodge Copper products in Bayway, New Jersey, and finally wound onto coils by Allis-Chalmers in Milwaukee, Wisconsin.

To increase their efficiency and output, the calutrons were fed with low-enriched uranium from the S-50 and, later, the K-25 Plant, both at Oak Ridge. A scaled-up version of the thermal diffusion pilot plant operated by the U.S. Navy at the Philadelphia Naval Yard, the S-50 Plant was built to take advantage of the excess steam produced by the K-25 Plant powerhouse. S-50 used concentric hot and cold pipes to provide the temperature difference needed to separate uranium isotopes. Built in nine months, S-50 fed low-enriched uranium to the Y-12 Plant Calutrons from March 1945 through September 1945.

Once technology problems relating to the development of an effective diffusion barrier material were overcome, the K-25 gaseous diffusion plant also produced LEU to feed the Calutrons at Y-12 beginning in March 1945. After the K-25 plant began to produce weapons-grade uranium in August 1945, the Y-12 electromagnetic plant was shut down.

Construction of the K-25 Plant was a major industrial effort. The Kellex corporation, of Jersey City, New Jersey, a subsidiary of the M. W. Kellogg Company designed the plant. Construction was managed by the J.A. Jones Construction Co. out of Charlotte, North Carolina, with the assistance of Ford, Bacon & Davis. The plant and equipment were created by companies from all areas of the country. The original K-25 converters (the corrosion-resistant tanks enclosing the diffusion barriers) were manufactured and assembled by the Chrysler Corporation in Detroit, Michigan. Half a million specialized valves were supplied by Crane Manufacturing Company while compressors designed to handle uranium hexafluoride were developed and supplied by the Allis-Chalmers Company based in Milwaukee, Wisconsin.

Uranium Enrichment Processes

Gas Centrifuge – The lighter uranium-235 isotope concentrates near the center of a spinning centrifuge of gaseous uranium UF_6, hexafluoride from which it can be removed. Using this method, the first gram quantities of enriched uranium were produced at the University of Virginia in 1941. An improved device was operated by Standard Oil at the Bayway Refinery, New Jersey in 1944. Westinghouse Electric manufactured the centrifuges in East Pittsburgh, Pennsylvania, and built a small centrifuge pilot plant in Bayonne, New Jersey. Engineering difficulties during WW II led to a decision to concentrate efforts on the other processes, although a pilot plant in Oak Ridge and a full-scale plant in Piketon, Ohio were built in the 1970s.

Thermal Diffusion – In the presence of a temperature difference, the lighter uranium-235 isotope will diffuse toward a hot area faster than the heavier uranium-238 isotope. Initially developed at the Naval Research Laboratory in the Anacostia section of Washington, DC, the Navy built a thermal diffusion pilot plant using concentric hot and cold pipes at the Philadelphia Naval Yard in 1944. Thermal diffusion was employed on a production scale at the S-50 plant in Oak Ridge, Tennessee, in 1945. The process provided LEU feed to the Y-12 electromagnetic process plant until the S-50 plant was closed in August 1945.

Electromagnetic Spectrograph – Scientists working at the University of California in Berkeley developed the electromagnetic enrichment process that was installed and operated at the Y-12 Plant in Oak Ridge, Tennessee, from late 1943 through the end of 1946. The process is based on the fact that ions of the heavier uranium-238 atoms are deflected less than the ions of the lighter uranium-235 atoms as they travel through a magnetic field. Electromagnetic enrichment was done in a device called a "Calutron," a modification of an early cyclotron. Uranium chloride salt was used for this purpose. Unlike the other uranium enrichment processes, the electromagnetic process is a batch process. The electromagnetic enrichment plant produced the first gram quantities of HEU in 1944. Using LEU feed from S-50 and K-25 in early 1945, the Calutrons supplied all the HEU for the "Little Boy" bomb detonated over Hiroshima, Japan.

Gaseous Diffusion – The gaseous diffusion process is based on the difference in rates at which uranium isotopes in the form of gaseous UF_6 diffuse through a porous barrier. Development of this barrier was the most significant obstacle to success. A small pilot cascade was operated in Pupin Hall at Columbia University in New York City. The Kellex Corporation of Jersey City, New Jersey designed the first gaseous diffusion plant. The full-scale K-25 gaseous diffusion plant (2,996 diffusion steps or stages) was completed and operational at Oak Ridge in August 1945. Before its completion, K-25 supplied some low-enriched feed for the Y-12 Calutron devices of the electromagnetic process. Large amounts of electricity are required to pump the UF_6 through the diffusion cascade and to remove the heat of compression.

The K-25 Gaseous Diffusion Plant enriched uranium for nuclear weapons and commercial reactor fuel from 1945 until 1987. When first built, the U-shaped K-25 building was one of the largest roofed structures in the world, covering nearly 43 acres. *K-25 Gaseous Diffusion Plant, Oak Ridge, Tennessee. June 12, 1982.*

The K-25 Gaseous Diffusion Process Building is half a mile long and 1,000 feet wide. It is comprised of fifty buildings four stories tall and arrayed in a U-shape. The lower floor, which once housed electrical equipment and process control panels, now stores hazardous and radioactive wastes and part of the DOE's stockpile of virgin and enriched lithium. *K-25 Process Building, K-25 Gaseous Diffusion Plant, Oak Ridge, Tennessee. January 9, 1994.*

Converter vessels in a gaseous-diffusion plant contain porous barriers that enrich uranium in gaseous form by separating out the atoms of uranium-235 from more-abundant uranium-238. Each of these vessels is a stage in the enrichment process, and there are a total of 5,122 stages at this plant. The more stages uranium hexafluoride gas passes through, the higher its enrichment becomes. *Unit 7, Cell 2, K-33 Demonstration Cell, K-25 Site, Oak Ridge, Tennessee. June 21, 1993.*
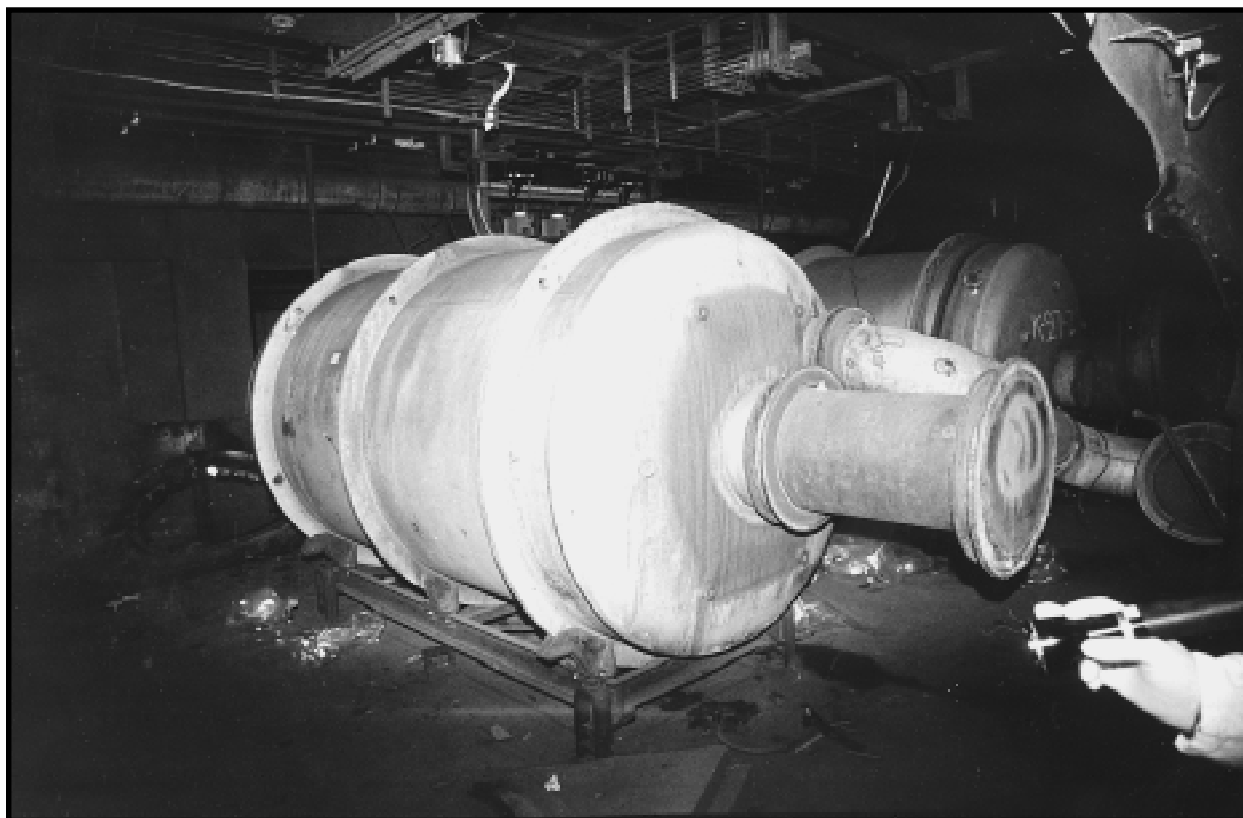
Partially-dismantled converter vessels used in the gaseous diffusion uranium enrichment process. *K-25 Building, Oak Ridge, Tennessee. January 12, 1994.*

Houdaille-Hershey Co. manufactured diffusion barriers at their Oakes Products Plant located in Decatur, Illinois. These diffusion barriers were made using nickel powder supplied by the International Nickel Co. plant in Huntington, West Virginia. Heat exchangers to remove the heat of compression were built by A.O. Smith Company in Milwaukee, Wisconsin and by Whitlock Manufacturing Company. Bart Laboratories, International Nickel, and Midwest Piping and Supply produced three million feet of special piping that could resist the corrosive effects of UF_6. Many other firms supplied pumps, instruments, gauges and other parts.

Post War Expansion of Uranium Enrichment – In September 1945, the Y-12 Calutrons and the S-50 thermal diffusion plant were shut down. Although they had proved effective during the war, the electromagnetic and thermal diffusion processes had several disadvantages. Calutron enrichment was a batch process, limiting its output and requiring considerable maintenance. The collectors had to be removed regularly so the enriched uranium product could be scraped out of them. The Calutron tanks and other equipment were periodically washed and cleaned to recover accumulated uranium from their surfaces. The Calutrons processed uranium in the form of uranium chloride salt, UCl_4. This salt oxidizes readily when exposed to air, which creates chemical processing problems in the Calutron feed and product material. Thermal diffusion was also inefficient. These difficulties contributed to the decision after the War to rely on gaseous diffusion, which allowed a continuous flow of uranium through the process.

To meet the projected demand for enriched uranium, AEC expanded the K-25 Gaseous Diffusion Plant beginning in 1946. Between January 1946 and June 1954, buildings K-27, K-29, K-31, and K-33—another 1,540 stages—were added to K-25, greatly increasing the plant's capacity. Expansion continued with the construction of two more gaseous diffusion plants. Peter Kiewit Sons' Company constructed the Portsmouth Gaseous Diffusion Plant, located in Piketon, Ohio, beginning in 1952. The plant, which features 4,080 stages in three buildings, was completed between November 1955 and February 1956. The Paducah Gaseous Diffusion Plant, in Paducah, Kentucky, was constructed between January 1953 and December 1954. F. H. McGraw and Company of Hartford, Connecticut was the general contractor. The Paducah Plant has 1,812 enrichment stages, housed in five buildings.

The three gaseous diffusion plants' output was nearly all highly-enriched uranium for the weapons program between 1946 and 1964. The plants also produced low-enriched uranium to be used as production reactor fuel during this period. Paducah was the feed point for the three plants and the low enriched Paducah product was split between the K-25 plant and the Portsmouth plant, which produced a variety of enrichments up to 97 percent. In addition to the functions of the diffusion cascade and the feed plant, K-25, Portsmouth and Paducah also cleaned and reconditioned the diffusion converters and other equipment.

The End of Weapons HEU Production and the Growth of Civilian Uranium Enrichment – AEC discontinued HEU production for weapons in 1964 because it had accumulated sufficient stocks. The K-25 and K-27 buildings at Oak Ridge were placed on standby at that time, and the remainder of K-25 was used to produce LEU. The gaseous diffusion plants continued to produce HEU after 1964 for other AEC programs, including civilian nuclear power research and the U.S. Navy nuclear power program. However, gaseous diffusion plant output dropped drastically for several years.

Gaseous Diffusion Plant output gradually increased again in the late 1960s to meet growing demand for enriched uranium for the commercial nuclear power industry. AEC and DOE sold uranium enrichment services to the commercial nuclear power industry. By the early 1970s, uranium enrichment plant output had risen back to its pre-1964 levels.

In the 1970s, DOE revived the development of the gas centrifuge enrichment process, and built a pilot plant at K-25 in Oak Ridge. The success of this project led to the construction of a full-size gas centrifuge plant at the Portsmouth Plant in 1977. However, to this date, the Portsmouth centrifuge plant has not operated at full scale. K-25 also supported the development of the Atomic Vapor Laser Isotope Separation (AVLIS) technology for uranium enrichment.

In 1992, Congress passed the Energy Policy Act and, under its provisions, uranium enrichment operations at the Portsmouth and Paducah Plants were leased by DOE to the newly-created United States Enrichment Corporation (USEC). The K-25 Plant was shut down in 1987, before the creation of USEC. At this time, USEC continues to operate the plants, although DOE has retained the responsibility for managing the environmental legacy left from prior operations.

Environmental Legacy of Uranium Enrichment – The three gaseous diffusion plants created a tremendous quantity of waste. Organic solvents, such as trichloroethylene (TCE), were used chiefly in the cleaning and maintenance of the enrichment plant equipment. Polychlorinated biphenyls (PCBs) were used as dielectric materials in the large electric power systems that powered the gaseous diffusion plant and in various gaskets and seals in plant equipment. From 1946 through 1987, estimated uranium releases from K-25 included 10,500 kg to the air, 16,700 kg to surface water, and 33,000 kg to on site land disposal. In addition, tens to hundreds of gallons or pounds of various volatile chemicals, like methylene chloride and fluorine, were released to the atmosphere though normal use.

The K-25 Site includes the K-1070-A contaminated burial grounds, where materials contaminated with uranium, thorium and their chemical compounds, UF_6, beryllium chips, boron, radioactively contaminated sodium fluoride, oil, plutonium, and arsenic were placed in unlined trenches, pits, and diked drum storage pads for waste oils and PCB wastes between the late 1940s and 1976. Also located at K-25 is the K-1070-C/D classified burial grounds, a 22-acre tract; the 1.3 acre K-1407-B holding pond, an unlined hazardous waste lagoon, used from the 1940s until the early 1980s for settling metal hydroxide precipitates from neutralized solutions; the K-1413 treatment facility, where groundwater was contaminated with solvents, radionuclides, and acid waste in the 1950s; and a number of contaminated scrap metal yards. Seventy thousand drums of sludge from the settling ponds have been solidified and removed.

Uranium enrichment is the largest contributor to the Department of Energy's materials in inventory. The Department stores depleted uranium enrichment "tails" at all three gaseous diffusion plants. Enrichment is also the major source of the Department's scrap metal inventory, including large amounts of steel, aluminum and nickel. This material results from the replacement and removal of enrichment process equipment.

Uranium enrichment plants have also resulted in some of the largest of the Department's surplus facilities. Although not as numerous as the facilities involved in other production processes, the gaseous diffusion plant buildings are very large, with many acres of floor space. Contamination in these facilities includes enriched uranium, PCBs, and asbestos.

Lithium Enrichment

Lithium enriched in the lighter lithium-6 isotope is used as a raw material for the production of tritium, and in weapons components in the form of lithium deuteride, a material which resembles a ceramic. The Oak Ridge Y-12 Plant began the initial effort to develop lithium isotope separation processes in 1950. Three processes were explored: COLEX, ELEX, and OREX.

The first successful laboratory separation was achieved with the ELEX process—an electrically driven chemical exchange process similar to that used in chlor-alkali plants for the manufacture of chlorine gas and sodium hydroxide. The ELEX pilot plant was built at Y-12 in 1951. Y-12 operated a production scale ELEX plant in building 9204-4 ("Beta 4") from 1953 until 1956. This plant was cleaned out and dismantled by 1959.

The OREX process, in which an organic solution of lithium was exchanged with a solution of lithium in mercury (called an "amalgam") never advanced further than the pilot plant stage. The OREX pilot plant in Y-12 Building 9202 was built in 1952 and subsequently dismantled between 1957 and 1959.

The COLEX process (the name is a contraction of "column exchange") is based on the fact that isotopes of lithium are partially separated when transferring between an aqueous solution of lithium hydroxide and

a lithium-mercury amalgam. The COLEX process supplied most of the enriched lithium needed for the weapons complex. AEC built two large COLEX facilities, called Alpha 4 and Alpha 5, in Buildings 9201-4 and 9201-5 at the Y-12 Plant. Alpha 4 operated from January 1955 until 1963. The unit was placed on standby until it was dismantled in the late 1980s. Alpha 5 began operating in 1955. It was shut down in 1959 and restarted in 1963 for a six-month campaign. Y-12 Plant engineers dismantled and disposed of the Alpha 5 COLEX process equipment in 1965 and 1966. Site contractors operated an open-air mercury receiving operation, where mercury flasks were emptied into a pipe leading to the COLEX plants, at the

Figure B-7. COLEX Process for Lithium Isotope Separation
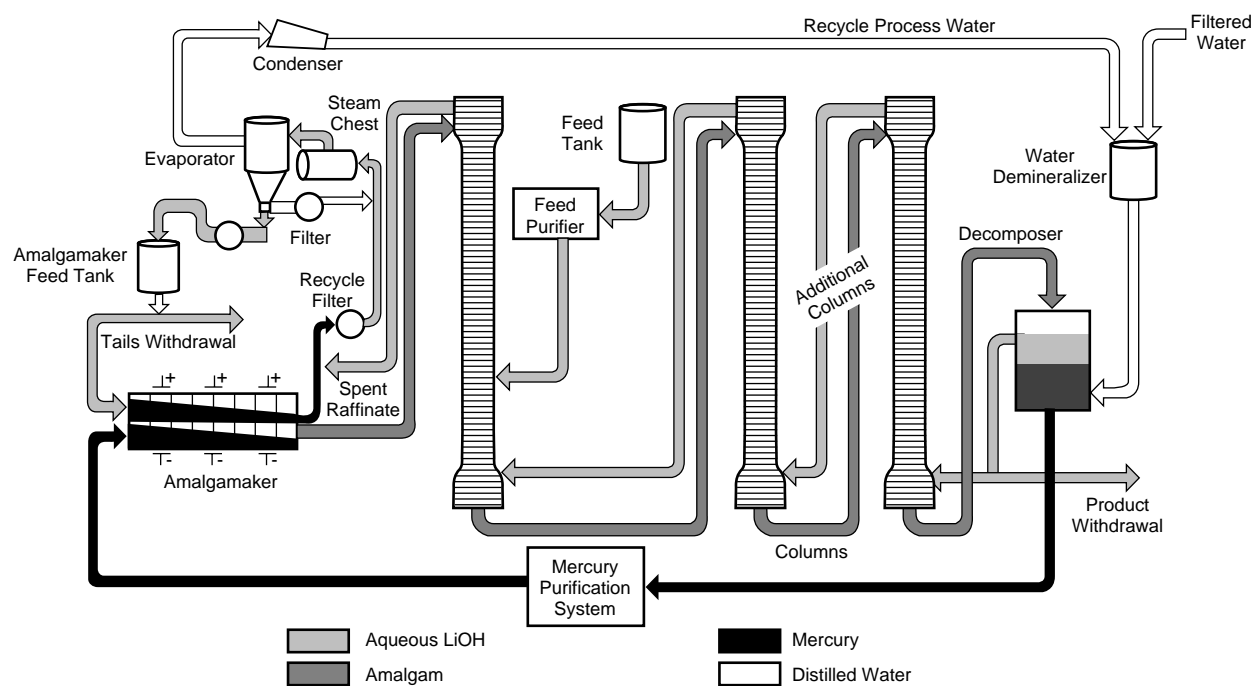
site of the current Building 9103. They used a furnace in a shed at the location of Building 81-10 to roast sludges, wastes and other materials for mercury recovery.

Lithium enrichment has created a considerable amount of materials in inventory. DOE stores the lithium enrichment "tails," depleted in the lithium-6 isotope, at the Portsmouth Plant and the K-25 Site. K-25 also stores a stockpile of unprocessed lithium. Y-12 and K-25 both store the Department's stockpile of enriched lithium.

The COLEX process employed approximately 24 million pounds of mercury. Most of the mercury used in the COLEX and ELEX processes was returned to the General Services Administration (GSA) once it was no longer needed. However, a great deal of mercury was lost in wastes, spills, and through evaporation. A mercury-nitric acid purification system utilized in the COLEX process between 1955 and 1960 was the source of the major mercury-bearing waste stream at Y-12. This system discharged a diluted, neutralized acid waste containing mercuric nitrate to East Fork Poplar Creek. Mercury vapor from the plant was exhausted to the environment by the building ventilation systems. Mercury from spills also contaminated basement sumps which were pumped through three concrete sedimentation tanks into the storm sewer and from there were pumped directly into East Fork Poplar Creek. DOE believes that small amounts of residual mercury are still present in the Y-12 Plant sewers. Inorganic mercury compounds of the type released at Y-12 plant were not initially believed to be toxic unless inhaled. It was not until 1970
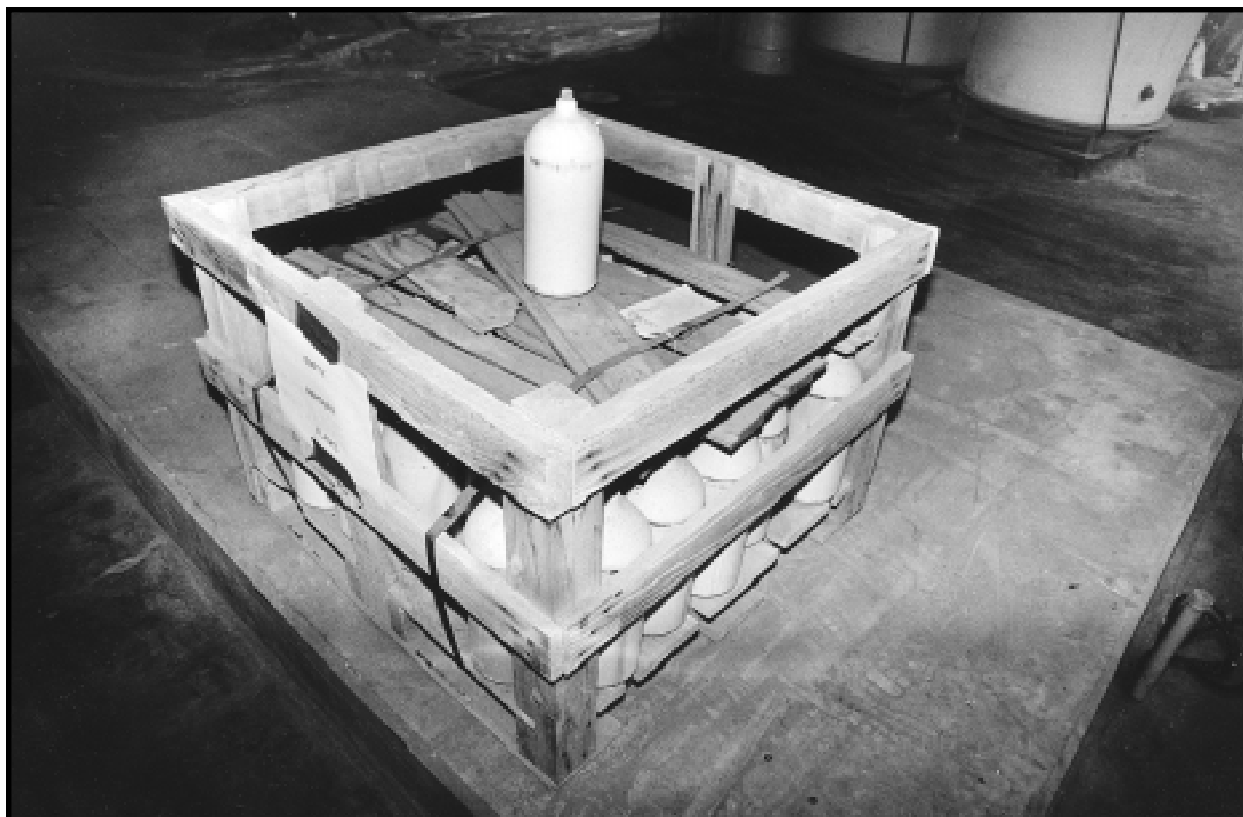
Flasks of mercury used for lithium enrichment at Y-12. Between 1951 and 1963, a significant fraction of the available world supply of mercury was used in this process. Approximately 730,000 pounds of that mercury is known to have been lost, spilled, or dumped into the environment around Oak Ridge, and for which an additional 1.3 million pounds are unaccounted. *Alpha 4 Building, Y-12 Plant, Oak Ridge, Tennessee. January 11, 1994.*

Lithium enrichment "tails," a byproduct of lithium enrichment at Oak Ridge, are stored at the Portsmouth and K-25 plants. The 30.8 million kilograms of lithium tails stored at Portsmouth are stacked from wall to wall and floor to ceiling in a series of "barns." DOE repackaged these materials in the 1980s after their original cardboard containers deteriorated. This lithium was sold to commercial buyers in 1996, and is gradually being shipped off site for use in batteries and other industrial applications. *Portsmouth Gaseous Diffusion Plant, Piketon, Ohio. 1986.*

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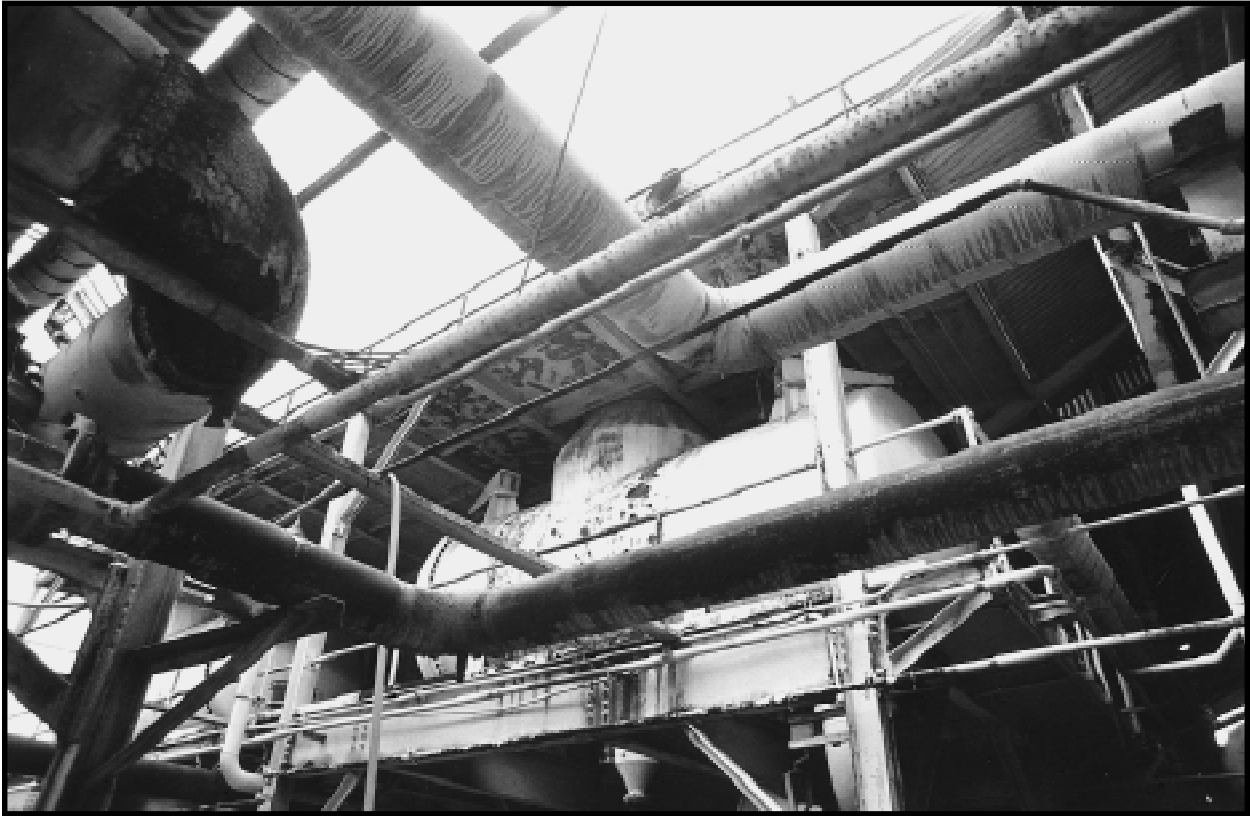
COLEX lithium-enrichment equipment. This plant was shut down in 1963. *Alpha 4 Building, Y-12 Plant, Oak Ridge, Tennessee. January 11, 1994.*

Reality Lake, originally named New Hope Pond, is located at the eastern end of the Y-12 Plant. Engineers created the lake in 1963 to alter the flow of East Fork Poplar Creek, which runs through the Y-12 site. Their aim was to reduce variations in the alkalinity of the creek water and limit the spread of chemical spills. Sediments containing mercury from Y-12 settled at the bottom of the lake rather than washing downstream into the Clinch River. Although this reduced the severity of contamination in the Clinch River system, it poses problems for the environment at Y-12, as the sediments of the creek and lake are severely contaminated. *Reality Lake, Y-12 Plant, Oak Ridge, Tennessee. June 15, 1993.*

that scientists discovered the biological methylation of inorganic mercury in the environment, which raised concerns over mercury discharges to surface water.

Approximately two million pounds of mercury used in the lithium enrichment processes have still not been accounted for. Approximately 730,000 pounds (about 4,000 gallons) of this material is believed to have been lost in waste streams, evaporation, and spills. A study done in 1983 estimated that evaporation during maintenance operations, seepage from pumps and other equipment, the venting of mercury vapors, and the smelting of mercury-contaminated scrap released 51,300 pounds of mercury into the air. The COLEX process discharged 239,000 pounds of mercury to East Fork Poplar Creek in the process waste stream, some of which is now in sediments at the bottom of New Hope Pond. DOE believes that these waste discharges are also the source of some of the mercury contamination in Watts Barr Lake, Poplar Creek and the Clinch River. However, these bodies of water are also downstream from a commercial chlor-alkali plant. Residual mercury contamination at Y-12 includes sludges and mercury residue in building sewers and drain systems. The 1983 study also estimated that approximately 425,000 pounds of mercury were lost to the soil in eight accidental spills at the Y-12 Plant.

Boron-10 Production

Boron-10 is a powerful neutron absorber with many uses in the nuclear weapons complex. The boron-10 production process uses a dimethyl ether-boron trifluoride complex. The complex is fed into a distillation system. When the complex is boiled, part of the vapor phase breaks down into boron trifluoride and dimethyl ether. Boron triflouride vapor molecules containing lighter boron-10 atoms reassociate into the liquid phase more rapidly than molecules containing the heavier boron-11 isotope. As a result, the heavier isotope is concentrated in the vapor phase and the lighter isotope in the liquid phase.

To supply boron-10, AEC built a plant in Model City, New York, near Niagra Falls. The plant operated from September 1954 until 1958, when AEC placed it on standby. The Model City plant was rehabilitated in mid-1964 and restarted. First, the restarted plant converted the remaining inventory of boron-10 from potassium fluoborate (KBF_4) to elemental boron to meet immediate weapon and reactor program demands. The plant continued to produce boron-10, until it was placed on standby again in March 1971 Since that time, the government has relied on commercial nuclear industry suppliers to convert its inventory of enriched boron-10 to a powder form, and to supply additional boron-10.
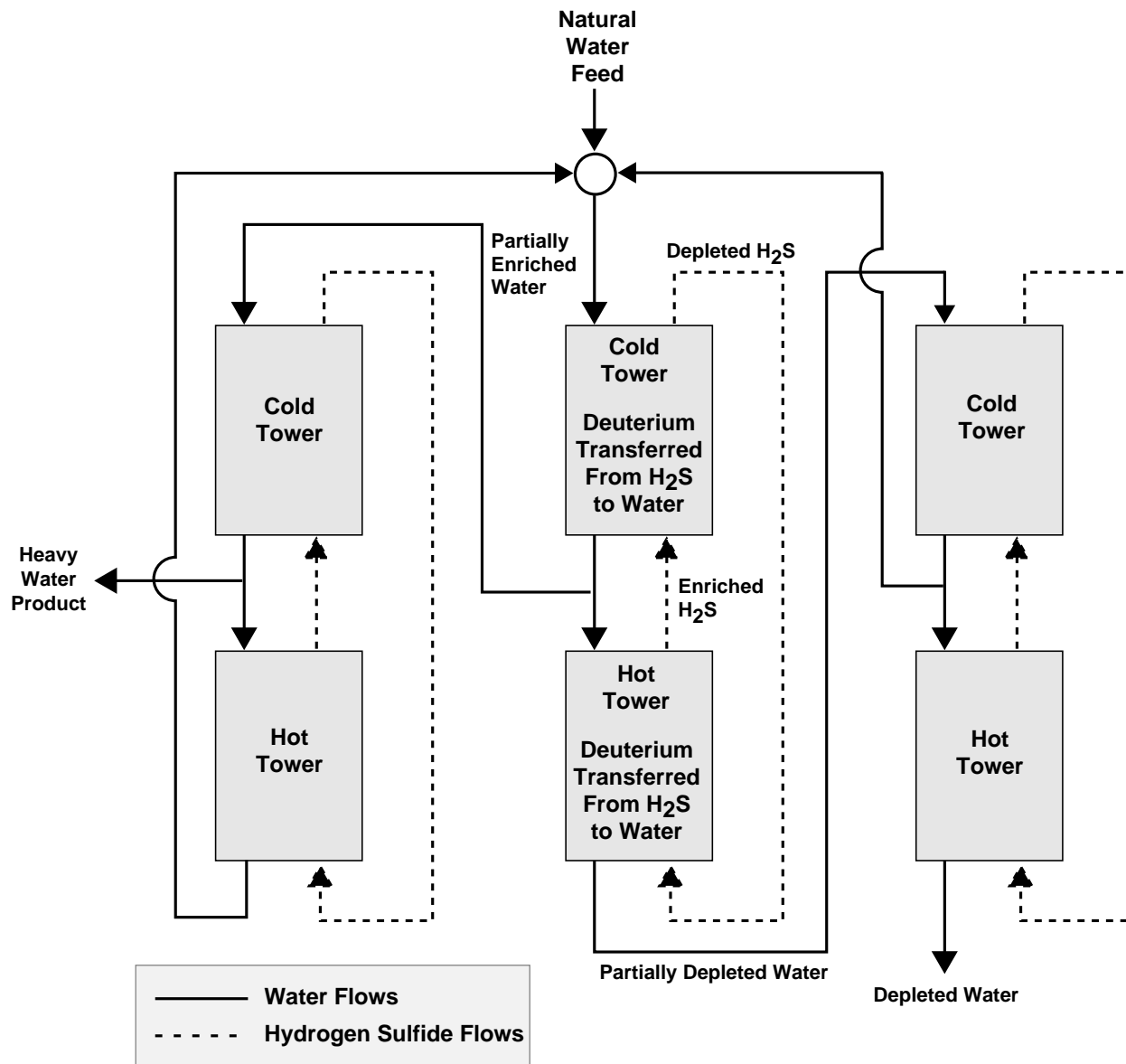
Heavy Water Production

Deuterium occurs naturally at a concentration of about 0.015 percent in the element hydrogen. This naturally occurring isotope was concentrated to produce pure deuterium in the form of "heavy water." Deuterium, has three major uses in the nuclear weapons complex due to its low neutron absorption and ability to undergo fusion to create heaver elements. Heavy water was used as a coolant and moderator in nuclear materials production reactors at the Savannah River Site. Deuterium separated from heavy water is combined with enriched lithium-6 to make ceramic-like lithium-6 deuteride parts for the secondary stages of thermonuclear weapons. Finally, a mixture of deuterium and tritium gases is injected into the "pit" of the primary (fission) stage of modern U.S. nuclear weapons to "boost" nuclear explosive yield.

Heavy water can be made using hydrogen sulfide-water chemical exchange, water distillation, or (in the earlier years) electrolysis. A description of the hydrogen sulfide process is contained in Figure B-8.

A small amount of heavy water was produced by electrolysis in the United States prior World War II. A plant operated by Norsk Hydro in Vemork, Norway was the world's major source of heavy water in the early 1940s. The first large heavy water plant in North America was built for the Manhattan Project by Standard Oil Co. at the Consolidated Mining & Smelting Company plant in Trail, British Columbia, Canada.

Most of the heavy water for the U.S. nuclear weapons programs was made at two sites. The Dana Heavy Water Plant in Newport, Indiana operated from April 1952 until May 1957, and remained on standby

Figure B-8. Heavy Water Enrichment Using the Hydrogen Sulfide Process

until July 1959. The Savannah River Site Heavy Water Plant in South Carolina began operating in October 1952, and after a staged shutdown, terminated heavy water production in 1982. Savannah River Site engineers finished dismantling the production plant in 1996.   Both sites used a combination of hydrogen sulfide-water chemical exchange, water distillation, and electrolysis processes. Degraded "half-heavy water" from dismantled weapons was recycled through the Savannah River Site Heavy Water Plant for re-enrichment. The Savannah River Heavy Water Plant continues to produce deuterium gas for nuclear weapons from existing heavy water stocks using an electrolytic process.
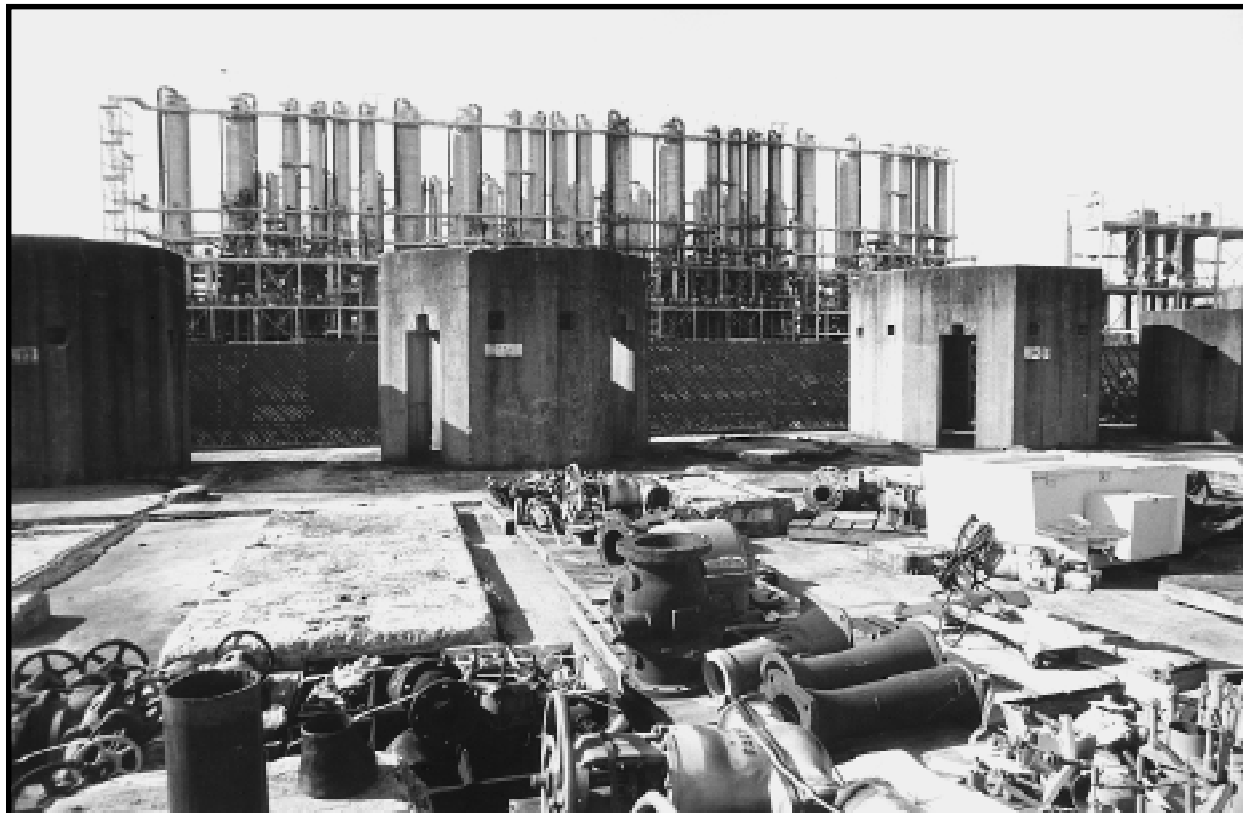
Savannah River Heavy Water Plant being dismantled. The plant seperated and concentrated the small fraction of deuterium found in ordinary water to produce "heavy water." Heavy water produced here between 1952 and 1982 was used in plutonium and tritium production reactor on the site and in nuclear weapons. *Heavy Water Extraction Facility, Savannah River Site, South Carolina. January 8, 1994.*

Heavy Water Production

Deuterium, which occurs naturally at a concentration of 0.015% in water, can be concentrated by several methods, all of which exploit the differences in chemical properties that result from the difference in the masses of the two isotopes.

Hydrogen Sulfide-Water Exchange – In a mixture of hydrogen sulfide (H_2S) and water at chemical equilibrium, the concentration of deuterium in water is greater than the concentration in H_2S. The difference in these concentrations depends on the temperature of the mixture. In practice, water and hydrogen sulfide gas are made to flow in opposite directions at two different temperatures. Deuterium is transferred from the gas to the water in the cold section. The depleted gas is recirculated to the hot section, where deuterium is transferred back into the gas from the water. Several stages of this process allow deuterium enrichments of up to 20-30%.

Fractional Distillation – Water molecules containing deuterium atoms vaporize at a higher temperature than those without deuterium, so the boiling point of heavy water is slightly higher than that of normal water. Water vapor above a mixture of normal and heavy water will be slightly depleted in deuterium as a result, while the liquid will be slightly enriched. Enrichment results from successively boiling off and removing vapor containing normal hydrogen.

Electrolysis – Water containing normal hydrogen is more easily disassociated into hydrogen and oxygen gases by an electric current than water containing deuterium. This allows the isotopes to be separated.

The Savannah River Site heavy water plant used the hydrogen sulfide-water exchange process to partially enrich heavy water. Deuterium was further concentrated by fractional distillation, and then by electrolysis. The moderator rework unit at SRS used fractional distillation to re-enrich reactor moderator that had become depleted in deuterium.

FUEL AND TARGET FABRICATION

Fuel and target fabrication consists of the foundry and machine shop operations necessary for the conversion of uranium feed material into the fuel and target elements used in nuclear materials production reactors. Included are the casting, extrusion, alloying, plating, cladding, machining, etching, cleaning, degreasing, and grinding to produce the finished elements.

Three basic types of production reactor fuel and targets were manufactured. Some of the production reactors used natural or low-enriched uranium as fuel. The uranium-235 in the fuel sustained the chain reaction while the uranium-238 in the fuel captured neutrons to produce plutonium. Other reactors used "driver fuel" (made with highly-enriched uranium) and separate targets (made of depleted uranium) for the same purposes.

In addition to uranium, various materials placed in the reactor cores ("targets") or around them ("blankets") absorbed neutrons to produce useful isotopes. Targets and blankets of lithium-6 were used to make tritium. Targets of thorium-232, neptunium-237, and bismuth-209 have been used to produce, respectively, uranium-233, plutonium-238, and polonium-210. DOE and its predecessors have irradiated many more target materials in small amounts to produce special isotopes, including thulium-170, iridium-192, lanthanum, plutonium-242, americium, curium, and californium.

Manhattan Project Reactor Fuel Manufacturing

The first nuclear reactors, including the three Chicago piles, the Oak Ridge X-10 reactor, and the Hanford B, D and F production reactors and 305 test pile, were built and operated by the Manhattan Engineer District of the U.S. Army Corps of Engineers. Because enriched uranium was not available in large quantities until 1945, and enrichment focused on producing highly-enriched uranium for weapons, Manhattan Project reactors used fuel made of unenriched natural uranium (NU) metal.

Metallurgical properties of uranium were unknown before the Manhattan Project. Most of the early uranium metallurgical research was accomplished from 1942 to 1943 at various research facilities including the University of Chicago Metallurgical Laboratory (known as the "Met Lab"), Iowa State College (now the Iowa State University) in Ames, Iowa, DuPont's Chambers Dye Works in Deepwater, New Jersey, Princeton University in New Jersey, and the Albany Research Center in Albany, Oregon.

The first self-sustaining chain reaction was achieved in a "pile" called CP-1 ("Chicago Pile 1) built by Enrico Fermi and his Met Lab colleagues under a squash court at the University of Chicago. "Fuel" for the pile consisted of lumps of uranium oxide and metal. Westinghouse Electric of Bloomfield, New Jersey, Metal Hydrides of Beverly, Massachusetts, and the Iowa State College supplied metallic uranium. Laboratory workers at the University of Chicago pressed uranium oxide, supplied by the Mallinckrodt Chemical Works in St. Louis, Missouri, into solid lumps. CP-1 was disassembled and rebuilt at the Palos Forest Preserve outside Chicago as CP-2; the uranium was reused.

Unlike the Chicago reactors, the Oak Ridge X-10 and Hanford reactors required cooling to dissipate the heat generated by their much greater power output. The X-10 reactor used air as a coolant, while the Hanford reactors, although originally designed to be helium cooled, were built to use cooling water from the Columbia River. Uranium fuel for these reactors had to be "canned" to prevent the release of highly radioactive fission products into the coolant and prevent corrosion of the uranium by the coolant.   The high power levels of the Hanford reactors called for uranium slugs to be "bonded" to aluminum cans to improve heat conduction from the slug to the cooling water, however, fuel for the Oak Ridge reactor was "unbonded." Due to problems with slug canning, MED manufactured "unbonded" Hanford slugs as a backup. These slugs later proved to be unsatisfactory.

Beginning in 1943, 14 private contractors and vendors produced fuel for the X-10 pilot plant reactor and the full-scale Hanford production reactors. Several contractors extruded, rolled, or drew uranium ingots into long rods that were subsequently straightened and outgassed (heated in an inert atmosphere).

Another group of contractors machined these finished rods into short slugs and ground, coated, bonded and canned them into finished uranium slugs. Hanford eventually manufactured its own fuel rods on site.

Engineers selected extrusion over rolling, drawing, forging, and other uranium rod fabrication methods. At the start of the extrusion process, workers preheated uranium billets in a rotary electric resistance furnace for about an hour. They quickly placed the hot billet into the extrusion container after brushing or flattening it as necessary to remove rough or swollen spots. A hydraulic ram pushing against a block at the back of the billet forced the hot metal through a die at high pressure. In about ten seconds, the extrusion press formed a 20 inch long, 200 pound billet into a 14 foot long rod. Workers quickly straightened and quenched the finished rod in water. They removed the unextruded "butt" end of the billet from the press and recycled it as scrap.

Between 1943 and 1946, the Revere Copper and Brass Company extruded uranium rods in its Detroit, Michigan plant. B&T Metals of Columbus, Ohio extruded a large quantity of uranium metal rods for Hanford from April through August 1943. Wolverine Tube in Detroit, Michigan extruded uranium for MED starting June 1943. As an alternative to extrusion, the Carpenter Steel Company of Reading, Pennsylvania experimented with rolled uranium rods in July 1944, but these proved to be inferior to the extruded product. Joslyn Manufacturing & Supply Company of Fort Wayne, Indiana also rolled uranium rods from billets starting in 1944 and continued until 1949. Uranium ingots began arriving at Hanford in November of 1944, however, extrusion there did not commence until January 1945.

A specialized machine tool performed the final straightening of uranium rods. Subsequently, workers heated the rods for several hours in an inert atmosphere to drive off gases (especially hydrogen) that are dissolved, combined or included in the metal. This process is called "outgassing." The Copperweld Steel Company of Warren, Ohio outgassed and straightened a large quantity of uranium rods for the Hanford and Oak Ridge reactors between May and August 1943. Revere Copper & Brass also outgassed and straightened rods in Detroit. Hanford began outgassing and straightening its own uranium fuel rods in September 1944.

Extruded or rolled uranium rods, 5 to 6 feet long and 1.425 to 1.475 inches in diameter, had to be cut and finished into eight inch long, 1.36 inch diameter slugs with tight tolerances. The slug machining process is straightforward. A machinist finishes one rough end of a straightened, outgassed uranium rod on a lathe. The machinist uses the lathe to reduce the rod to the proper diameter, cut off a slug, finish the cut end of the slug, and round off the corners. During this process, a large flow of coolant (a water and oil mixture) prevents the uranium chips and turnings from igniting.

Before 1942, nobody had ever machined metallic uranium. Summerville Tubing Co., Wycoff Drawn Steel Co., International Register Co., and Globe Steel (locations unknown) initially developed uranium machining techniques in 1942 and 1943.

Hanford began machining uranium rods in December of 1943. Baker Brothers of Toledo, Ohio machined 130 tons of uranium rods from Revere Copper and Brass into slugs, filling most of the initial fuel requirement for the Oak Ridge graphite reactor between June and October 1943. Baker Brothers also manufactured unbonded uranium slugs for Hanford from early 1944 until July of that year. C.H. Schnoor (Springdale, Pennsylvania) machined unbonded Hanford slugs from metal rods between May and July 1944. The Herring-Hall-Marvin Safe Company in Hamilton, Ohio machined uranium slugs from rolled rods in the 1940s to the early 1950s. American Chain & Cable Co. in Bridgeport, Connecticut swaged uranium rods (i.e., reduced their diameter) in 1944. The William E. Pratt Manufacturing Co. (a subsidiary of Joslyn Manufacturing & Supply) machined slugs for CP-1 in the spring of 1943 and, in the spring of 1944, turned and ground unbonded Hanford slugs. Subsequently, between May and August of 1944, McKinney Tool & Manufacturing in Cleveland, Ohio turned and ground unbonded Hanford slugs.

Development of sealed cans that would allow sufficient cooling of the uranium slugs was a difficult task. Alcoa in New Kensington, Pennsylvania sealed the slugs for the X-10 reactor into unbonded aluminum

cans. Experimental, unbonded Hanford slugs were canned by the Quality Hardware & Machine Corporation of Chicago, Illinois in the summer of 1944.

The slug canning process for Hanford was developed by DuPont at the Grasselli Laboratory in Cleveland, Ohio. Hanford's "triple dip" slug coating and canning process for bonding the uranium slugs to the cans started in March 1944. The original fuel elements for the Hanford reactors were solid uranium cylinders encased in aluminum cans. Uranium slugs were cleaned with nitric acid, then successively bathed in molten bronze, tin and an aluminum-silicon mixture. After water quenching, the sleeve was removed from the element, the aluminum end cap was machined and brazed on, and the finished element was etched in nitric acid. Steel sleeves surrounding each can were cleaned in sodium hydroxide. Aluminum caps and cans were cleaned in a sodium dichromate solution, followed by a methanol dip and air drying. Three tests followed. First the element was sprayed with acenaphtelene mixed with carbon tetrachloride and heated to test the bond between the core and can. Next the acenapthelene was removed with trichloroethylene and the canned element was heated in a steam autoclave in Building 314 to test for leaks. Finally, the element was radiographed (x-rayed) to check the porosity of the weld.

Fuel manufacturing produced scrap in the form of chips and turnings from the lathes, rejected fuel slugs, the "butts" from the extrusion process, uranium oxide, and acids and sludges from the slug, cap, sleeve, and can pickling, cleaning, and recovery processes. Uranium scrap processing was initially centered at the Metal Hydrides plant in Beverly, Massachusetts, which recast uranium scrap from 1943 until 1947.

Uranium metal reduction. A Fernald metals worker guides a cylindrical steel reaction vessel containing new uranium metal away from a bank of furnaces toward a cooling area. To convert into a metal, workers mixed green uranium salt crystals with magnesium granules in these reaction vessels, then heated them in a vacuum induction furnace for several hours until molten uranium metal was formed. Once the cylinder cooled, workers would remove the solidified uranium metal, re-melt it, and cast it into a cylindrical ingot. *Plant 5, Metals Production Plant, Feed Materials Production Center, Fernald, Ohio. December 16, 1985.*

Sampling the Derby. A Fernald metals worker collects metal shavings from a new uranium derby. She will send them to an onsite laboratory which confirms the isotopic content and purity of the metal. *Plant 5, Metals Production Plant, Feed Materials Production Center, Fernald, Ohio. December 17, 1985.*

Fernald Laundry. At the Fernald site, over 1,000 pairs of cotton work suits were laundered daily to rid the clothing of uranium dust. Laundry water was treated as low-level radioactive waste because of its uranium content. *Feed Materials Production Center, Fernald, Ohio. December 16, 1985.*

Post-War Development of Fuel Fabrication

After the end of the war, Hanford manufactured its own reactor fuel for a few years using uranium metal ingots supplied from off site. However, slug manufacturing shifted off site again in the late 1940s and early 1950s. Hanford stopped extruding uranium rods in 1948, switching to rolled rods from off-site suppliers. In 1950, Hanford began making rolled uranium rods on site, but AEC shifted the rolling work to the Fernald, Ohio Feed Materials Production Center and its supporting contractors in 1952. During the late 1940s and early 1950s, uranium rods were rolled or extruded by Vulcan Crucible Steel Company in Aliquippa, Pennsylvania, Revere Copper and Brass, and the Brush Beryllium Company in Detroit, Joslyn Manufacturing & Supply Company in Fort Wayne, Indiana, Allegheny-Ludlum Steel Corporation in Watervliet, New York, and Simonds Saw & Steel Co. of Lockport, New York.
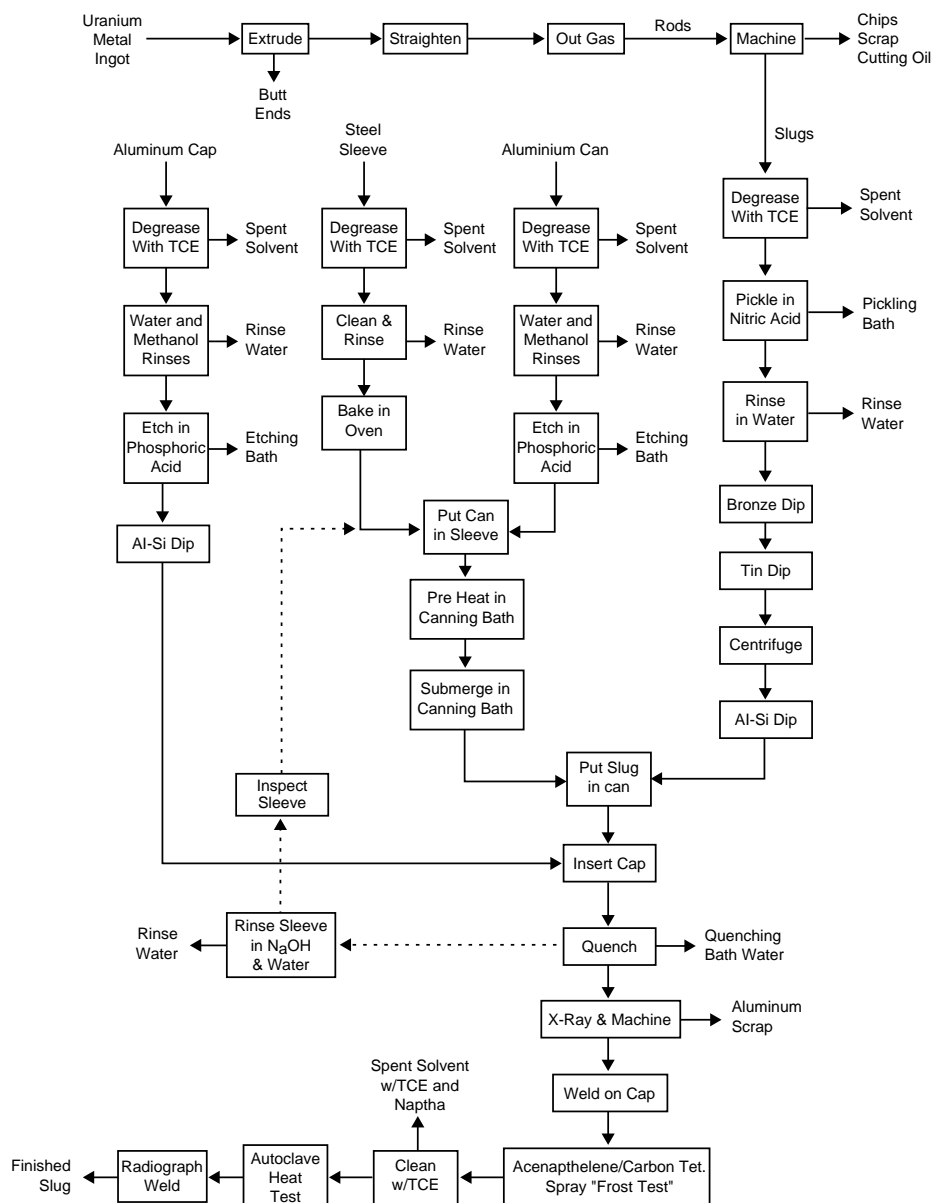
To increase plutonium production capacity, Hanford began adding low-enriched uranium fuel slugs to its reactors as early as 1950. Enriched uranium fuel also allowed Hanford engineers to even out the reactor's temperature and power distribution, reducing problems caused by uneven thermal expansion and radiation-induced swelling of the graphite core. Neutron absorbing "poison"

Uranium ingots were machined into billets on a lathe at Fernald. The shiny ingots have been machined while the dull ones have not. *Fernald Feed Materials Production Center, Ohio. December 17, 1985.*

slugs, also made on site, also helped to even out the reactor's power distribution. Most of these enriched uranium slugs were manufactured using the same techniques as the natural uranium slugs. However, some of the fuel elements were made of highly-enriched uranium alloyed with aluminum, which required special fabrication techniques to prevent accidental criticalities. These "driver" elements were often used in combination with special targets such as the lithium targets used to make tritium. Improvements in fuel slug design gradually reduced the tendency of the fuel slugs to become misaligned inside the reactor.

Fernald and Weldon Spring

AEC greatly expanded the number of production reactors in the weapons complex in the late 1940s and early 1950s. By 1955, a total of thirteen AEC production reactors were in operation: eight at Hanford and five at Savannah River. To supply fuel for these new reactors, AEC established the Feed Materials Production Center in Fernald, Ohio, in 1951. Fernald's sister facility, the Weldon Spring Plant near St. Louis, Missouri, opened in 1956. In addition, commercial contractors continued to support AEC's fuel fabrication needs throughout the 1950s.

AEC improved its reactor fuel manufacturing technology with the help of several contractors. Bethlehem Steel, in Lackawanna, New York, developed improved rolling mill pass schedules in 1949 to be used at the

Figure B-9. Fabrication Process for Hanford Reactor Fuel, 1945 to 1954


Fernald plant. Developmental work using rolling mills to make uranium rods was also done by Allegheny-Ludlum Steel in Dunkirk, New York between 1950 and 1952. Starting in 1954, Bridgeport Brass Company in Bridgeport, Connecticut (at a facility known as the Havens Laboratory) and Adrian, Michigan, worked to improve the extrusion process. In 1961 and 1962, the large extrusion press used for semi-production work at Adrian was dismantled and transported to the Ashtabula, Ohio Reactive Metals, Inc. plant where it was permanently installed. Work at the Bridgeport laboratory continued, moving to Seymour, Connecticut in 1962.

Extrusion and Machining – FMPC and Weldon Spring produced ingots of natural, low-enriched and depleted uranium to be extruded off site into tubes and billets for further machining into the uranium cores and shipment to the Hanford and Savannah River sites for cladding and assembly. The extrusion was performed by Bridgeport Brass Co. in Adrian, Michigan from 1954 to 1961 and then by its corporate successor, Reactive Metals, Inc., in Ashtabula, Ohio. Fernald also housed its own rolling mill. Figure B-10 provides a schematic of the production processes as they were performed at Fernald in the 1980s.

Figure B-10. 1980s Extrusion and Machining Production Process at Fernald

Metals Fabrication Process Flow
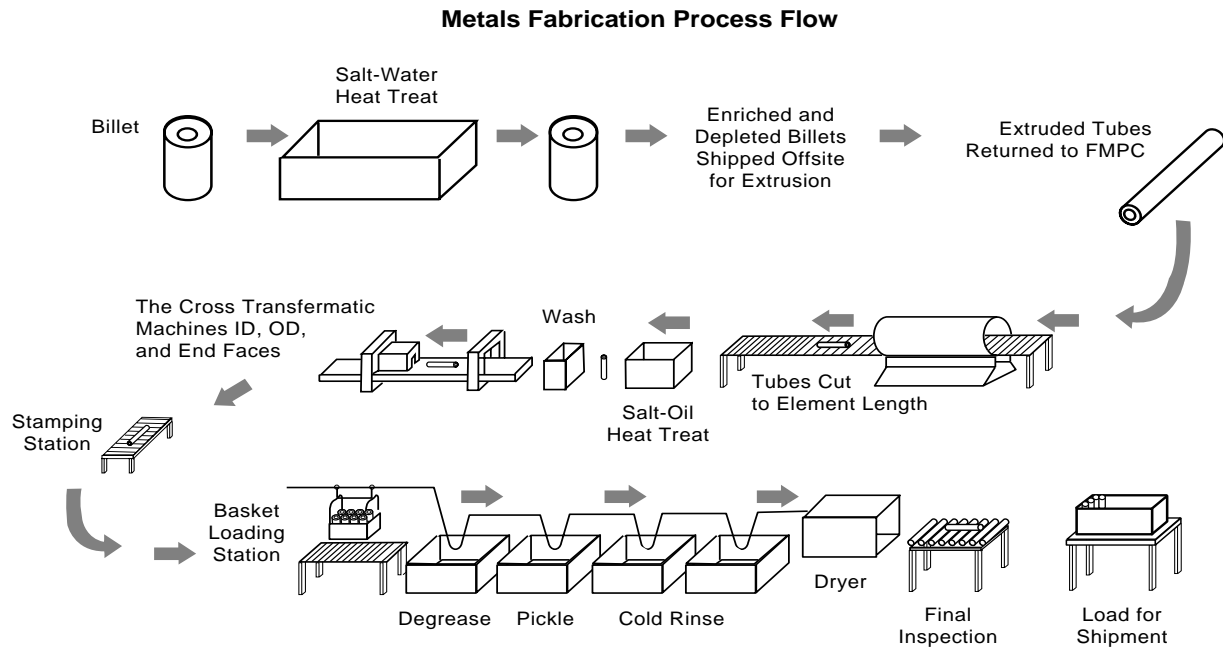
Note: Chips and lathe turnings from machining are crushed, pickled, rinsed, dried, formed into briquettes, and re-cast.
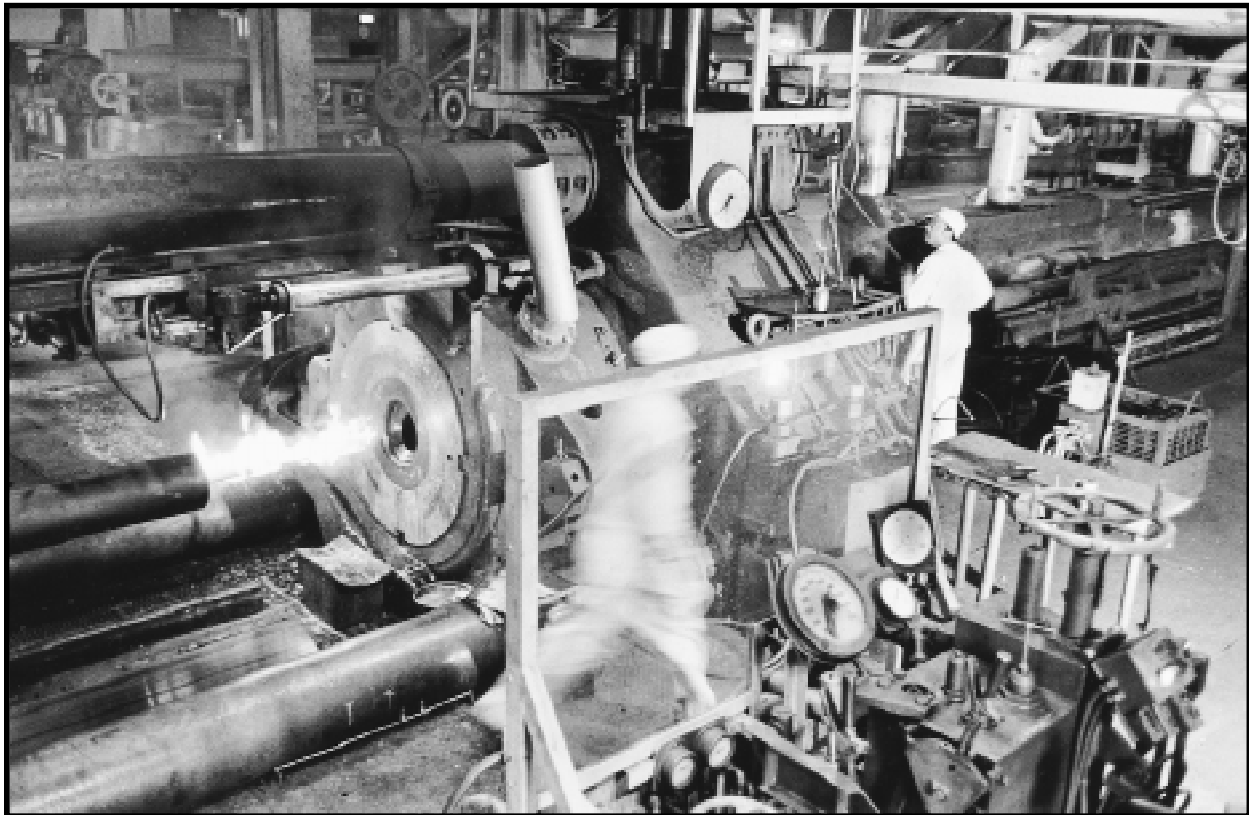
Ashtabula uranium metal extrusion press. This press extrudes red hot uranium ingots into long tubes. The uranium tubes were shipped back to Fernald where they were cut into fourteen inch lengths. These segments were then sent to South Carolina where they will be bombarded with neutrons and transformed into plutonium. *Reactive Metals, Inc., Ashtabula, Ohio, June 19, 1984.*

Along with many of the extrusion plants and rolling mills mentioned above, American Brass Co. of Waterbury, Connecticut, extruded copper-clad uranium billets for the Savannah River Site in the late 1950s, using copper-plated billets supplied by Nuclear Metals, Inc. Granite City Steel, located in Granite City, Illinois, x-rayed uranium ingots to detect metallurgical flaws for Weldon Spring from 1958 until 1966. Dow Chemical in Madison, Illinois, researched and developed extrusion techniques in 1957 and straightened uranium rods for Weldon Spring in 1959 and 1960. A number of contractors provided uranium slug machining services: Bliss & Laughlin Steel of Buffalo, New York; Alba Craft Laboratory of Oxford, Ohio; and Associated Aircraft and Tool Manufacturing, Inc. of Fairfield, Ohio.

Slug Cladding and Assembly – Except for the periods from 1944-1948 and 1950-51, Hanford received all of its uranium slugs from off site suppliers. With the exception of the experimental (and unsatisfactory) unbonded slugs produced in 1944, slug cladding and fuel element assembly have always been a mission of Hanford's 300 Area. Similarly, the Savannah River Site always received uranium slugs from off site suppliers, but cladded and assembled them to produce completed fuel elements in the M Area.

Hanford Fuel Improvements – Beginning in 1954, the solid cylindrical fuel rods were replaced with "cored" fuel rods, in which the uranium cylinder was drilled lengthwise to allow for expansion during irradiation and sealed into aluminum cans with closed ends. Also in 1954, Hanford switched to a new, lead-dip process for canning the fuel. The process consisted of immersing the uranium fuel cores in a bath of molten lead covered with molten aluminum, followed by a molten aluminum-silicon bath. At about the same time, the bonding test was changed, eliminating the use of acenapthelene and carbon tetrachloride. Between 1955 and 1964, about 30,000 single-pass reactor fuel elements were canned each week. A "hot die size" process involving nickel plating which incorporated nickel sulfate, nickel chloride, and boric acid was developed in the early 1960s, but never implemented on a large scale.

By 1957, the cored fuel rods were supplanted by tubular "I&E" fuel rods which allowed cooling water to run down the middle as well as around the outside. Various fuel slug improvements were tested, including changes in end designs, cladding materials and processes, and end cap welding. Eventually Hanford adopted "tru line" fuel elements with male and female ends to prevent misalignment of the fuel elements in the reactor.

N Reactor Fuel Fabrication at Hanford – The Hanford N Reactor used slightly enriched uranium fuel. Fernald and Weldon Spring produced the enriched uranium ingots and sent them to Ashtabula to be extruded into tubular billets. Fernald then shipped the billets to Hanford, where they were clad with zirconium into finished fuel assemblies using the coextrusion process. By the time of the start-up of the N Reactor at Hanford in late 1963, there were sufficient stocks of enriched uranium at FMPC to supply it without additional uranium from the gaseous diffusion plants. Hanford also chemically recycled enriched uranium from its own fuel, and enriched "mined" uranium for reactor fuel from the high-level waste tanks on site, using the U Plant. Enriched uranium from the gaseous diffusion plants was not needed for Hanford until 1985, shortly before N Reactor was shut down.

The coextrusion process for fabricating N Reactor fuel was developed in Building 306 (known locally as the "Met Semi-Works") and implemented in the 333 Fuels Manufacturing Building. Copper and copper-silicon preshapes and backing plates were inspected and cleaned with nitric, nitric hydrofluoric, and chromium nitric sulfuric acid. Next, zircaloy-2 cladding materials (an alloy of zirconium with nickel, tin, chromium and iron) were degreased in an organic solvent, rinsed with nitric and hydrofluoric acid, and air dried. The uranium billets were degreased with perchloroethylene, etched with nitric acid, rinsed with water, dried, and inspected. The uranium, copper, and zirconium parts were assembled and welded, tested, heated and extruded together. The extruded elements were cooled, cut, and machined. Nitric acid rinses removed copper and silicon residues and nitric sulfuric acid chemically milled away excess uranium on the ends of the slugs. A final nitric and nitric hydrofluoric acid etching preceded the brazing on of the end caps. The end caps were degreased and etched as well. After additional finishing, the parts were given a final etching in nitric hydrofluoric acid, tested, and assembled. This process reached a peak volume of 250 fuel elements per week in the mid-1980s.

Miscellaneous Target Fabrication at Hanford – Hanford made lithium-aluminum alloy targets between 1949 and 1952 as part of the P-10 tritium production project. (Tritium was called "coproduct" at Hanford.) From 1965 to 1967 the site again manufactured lithium aluminum target inserts, this time for the N Reactor. To make polonium-210, Hanford's 300 Area manufactured lead-bismuth alloy targets (called "B Metal") and welded them into unbonded aluminum cans, from 1944 to the early 1950s. The site's reactors used lead-cadmium fuel elements in nonbonded aluminum cans, made on site, as "poison" elements until 1971. In the 1940s engineers at Hanford investigated thorium poison slugs (called, "myrnalloy") and thorium targets reappeared in the 1950s for experimental uranium-233 production. Hanford also manufactured a variety of aluminum spacers used to hold the fuel rods in position inside the cooling water tubes from the late 1950s to 1971. The spacers were electrolytically anodized to create a protective aluminum oxide coating. Beginning in the mid-1960s, Hanford made passivated steel spacers for the N Reactor.

Savannah River Site M Area – M Area at the Savannah River Site manufactured fuel for the Savannah River Site reactors beginning in 1954. The five SRS reactors originally were fueled with aluminum-clad NU slugs which served as both fuel and targets. These slugs, and the manufacturing processes, were similar to those at Hanford.

To increase production capacity and operational flexibility, SRS converted in 1968 to HEU fuel using recycled enriched uranium. HEU metal from Y-12 was received at the SRS M Area, alloyed with aluminum, and extruded into aluminum-clad assemblies. After 1968, the SRS M Area also received depleted uranium metal slugs from FMPC and bonded them into tubular metal cans to be used as plutonium production targets. Enriched lithium (Li-6) received from Y-12 in sealed aluminum cans was alloyed and clad with aluminum for use as tritium production targets.

Shutdown of DOE Fuel Fabrication

Weldon Spring shut down in 1966 after losing a direct competition with Fernald. Buildings 313 and 314 at Hanford, which made fuel for the eight single pass reactors, shut down in 1971, and the equipment was removed from the mid-1970s to the mid-1980s. The N Reactor coextrusion process was discontinued in December 1986 when N Reactor shut down.

Fernald and the Savannah River Site M Area continued to manufacture reactor fuel after Hanford's reactors closed. However, they too shut down in 1989, when the Savannah River Site's reactors ceased operating for environmental and safety upgrades. With the exception of a brief restart of one reactor, SRS never resumed production, and the temporary shutdowns of Fernald and the Savannah River Site M Area became permanent.

Post-War Uranium Scrap Processing and Recycling

Uranium was scarce and expensive during the Manhattan Project and enriched uranium, even more so. Even after considerable domestic and world supplies of uranium were discovered in the mid-1950s, enriched uranium remained a precious commodity. Hence, recovery of uranium from process effluents, scrap, and other waste was a priority in the nuclear weapons complex.

Hanford began recycling uranium scrap on site in 1946. Chips of uranium metal from slug machining were sorted, washed, and pressed into briquettes. Uranium metal chip fires were a common problem. At first, the briquettes (and presumably other materials) were sent to Metal Hydrides in Beverly, Massachusetts, to be recast, but in May 1946, the briquetting was halted. In 1947, a "melt plant" was set up in the Hanford 300 Area. The melt plant melted the scrap metal with new uranium metal and recast the metal into ingots to feed the fuel manufacturing process. Another plant at Hanford began oxidizing various solid uranium-bearing materials and shipping them off site in five gallon buckets. Both the melting and oxidizing operations at Hanford were phased out between 1952 and 1954.

Crates of depleted uranium Mark 31 Target cores await shipment to the Savannah River Site where they would be bombarded with neutrons and partially transformed into plutonium. *Fernald Feed Materials Production Center, Fernald, Ohio. December 17, 1985.*

Fernald eventually began to receive and recycle unirradiated uranium scrap from fuel fabrication. After 1954, the scraps and residues from the Hanford fuel fabrication processes were filtered, slurried into sodium diuranate, and shipped to the Fernald plant.

A number of private contractors processed unirradiated uranium scrap for AEC in the 1960s, including the Davidson Chemical Company division of W.R. Grace and Company (later part of Nuclear Fuel Services, Inc.) in Erwin, Tennessee; Nuclear Materials and Equipment Corporation (NUMEC) of Apollo, Pennsylvania; United Nuclear Corporation in Hematite, Missouri and New Haven, Connecticut; National Lead Company in Albany, New York; Kerr-McGee Corporation located in Guthrie, Oklahoma; and General Atomics of La Jolla, California.

Fuel Fabrication Waste Management

Fernald and Weldon Spring – Waste from fuel and target fabrication and scrap recycling at the Fernald and Weldon Spring plants was managed in the same manner as the waste from uranium refining. Fernald disposed of solid and slurried waste in seven pits, a clearwell, two lime sludge ponds, and a sanitary landfill. Treated liquid waste flowed into the Great Miami River. Weldon Spring used a nearby quarry and four waste lagoons (called "raffinate pits") to store contaminated residue and waste from the plant.

Hanford 300 Area – Fuel fabrication at Hanford generated a considerable amount of waste, particularly acidic liquid waste from fuel slug can, cap and sleeve cleaning and testing, and uranium scrap processing. From the beginning of its operations, Hanford 300 Area discharged waste acids (nitric, sulfuric, hydrofluoric, and chromic nitric sulfuric) containing uranium, zirconium, copper, beryllium, and other materials, to an underground tank containing limestone, then to percolation ponds through a process sewer. Radioactivity levels in the original process pond, which covered 490,000 square feet to a depth of five feet,

rose by three orders of magnitude been 1945 and 1948, including a September 1947 spike from a large release of uranyl nitrate hexahydrate.[3]

The original process pond dike broke on October 25, 1948, spilling most of the pond's contents into the Columbia River. Following this accident, a new process pond was built to the north of the original pond, and the two ponds were used in tandem. Periodically, sludge from the ponds was dredged to recover uranium. In 1955, 10,300 pounds of uranium were recovered from a 9-inch deep swath of sludge taken from the bottom of the North Process Pond. The 300 North cribs were built in 1948 to allow UNH, ammonium nitrate, hexone, and other solvent wastes to percolate into the ground. These cribs received liquids containing 2,070 pounds of uranium by 1956. The Process Ponds were phased out in 1974 and 1975, and replaced by the 300 Area Process Trenches and the Waste Acid Treatment System.

In 1973, the Waste Acid Treatment System began operation at Hanford. This facility neutralized waste acids (approximately 210,000 gallons annually) with sodium hydroxide, and it centrifuged and filtered them to remove the resulting solids. Solids were then drummed and disposed of at the Hanford site. Tanks held the remaining liquid effluents, which were trucked to large, open solar evaporation basins in the 100-H reactor area until 1975. From 1975 until 1985, the effluents were disposed in the 300 Area Process Trenches. After 1985, Hanford took these liquids to the 200 Areas or shipped them off site for disposal. Rinse water, process water, cooling water, and steam condensate continued to be discharged to the process sewer. Several spills and leaks of process water occurred, including a June 1978 spill of 19,000 gallons of waste etching acid. At least six solid waste burial grounds were used in the Hanford 300 Area.

Savannah River Site M Area – From 1954 until 1958, waste effluents from metal-forming, electroplating and cladding activities, which contained metal degreasing solvents, acids, caustics, and metals, were discharged to the Tims Branch stream. In 1958, AEC authorized the construction of the M Area settling basin for waste streams containing enriched uranium. Some additional effluents were diverted from the Tims Branch outfall to the settling basin in 1973. After the Tims Branch stream outfall was closed in May 1982, all M Area effluents were diverted to the settling basin. However, in November 1982, most process effluents which did not directly contact the uranium and other radioactive materials (such as cooling water and surface drainage) were diverted back to the Tims Branch outfall. The Savannah River Site discontinued usage of the M Area Settling Basin in July 1985 when the Liquid Effluent Treatment Facility became available. Areas contaminated by wastes from the Settling Basin include the basin itself, the overflow ditch, the natural seepage area, a bay known as Lost Lake, and the inlet process sewer line.

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[3] *Uranyl nitrate hexahydrate, chemical formula $UO_2(NO_3)_2 \cdot 6H_2O$, is usually abbreviated as UNH*

REACTOR OPERATIONS

Reactor operations include fuel and target loading and removal, reactor maintenance and modification, and the control and cooling of the reactor as it operates. Large production reactors provide the neutrons needed to produce nuclear materials in large quantities. Smaller reactors are used to test materials and perform experiments.

Operating a nuclear reactor creates highly radioactive materials—spent nuclear fuel and irradiated targets. The structures of the reactor core and the reactor coolant also become radioactive. Most of the radioactivity in the DOE weapons complex was created in production reactors.

Manhattan Engineer District Reactor Operations

Seven nuclear reactors operated in the United States before and during World War II for the purpose of reactor research and nuclear materials production. Under contract to the U.S. Army and in cooperation with the University of Chicago, the E. I. du Pont de Nemours Corporation of Wilmington, Delaware, designed the Manhattan Project reactors and managed the procurement of the materials they required.

The Chicago Piles – The first reactor, which proved that a self-sustaining nuclear fission chain reaction was possible, was the Chicago Pile (CP-1) built by Enrico Fermi and his associates at the University of Chicago. CP-1 began operating on December 2, 1942. The reactor was fueled with lumps of natural uranium metal and oxide in a moderator matrix of graphite blocks. Forty tons of graphite for the reactor were supplied by the United States Graphite Company and machined at the MetLab. Denser, purer graphite came from the National Carbon Company. CP-1 had no cooling system and produced only a few

L-Reactor, Savannah River Site. Mark 31 target cores from Fernald were loaded into this reactor and bombarded with neutrons, which transformed some of the depleted uranium metal into plutonium. In front of the reactor are three reservoirs of cooling water. The Savannah River Site had a total of five plutonium production reactors. *L Area, Savannah River Site, South Carolina. August 6, 1983.*

watts of power. Recovery of any plutonium produced in the reactor was possible only after complete dismantlement.

By March 1943, CP-1 had been dismantled and rebuilt with modifications as CP-2 at the Palos Forest Preserve outside of Chicago. This location was code-named "Site A." CP-2 was larger than CP-1 and featured five feet of shielding to protect the scientists from radiation exposure. A heavy-water reactor, built for research on reactor physics, started up at Site A in May 1944. This reactor was called "CP-3."

After the war, reactor research in Chicago continued. The newly organized Argonne Laboratory was relocated its present site southwest of Chicago in January 1947. Today, Argonne National Laboratory is one of the Department of Energy's multi-program research laboratories. In 1956, AEC directed the shutdown of CP-2 and CP-3, still operating at Site A. Uranium, graphite, and heavy water were removed from these reactors, and the remaining shells were buried in a nearby area known as "Plot M."

Clinton Pile (X-10) – To test the principles of reactor operation and plutonium separation, the Manhattan Engineer District built a "semi-works," code-named "X-10." Originally planned for the Chicago area, MED relocated the semi-works to the more isolated area of eastern Tennessee known then as Clinton, now called Oak Ridge, for safety and security reasons. The X-10 reactor (also called the Clinton Pile or the "Graphite Reactor") was the pilot plant for large plutonium production reactors soon to be built at Hanford, Washington.

X-10 consisted of a cube of graphite moderator 24 feet on each side, fueled by aluminum-clad natural uranium cylinders fed and discharged through 1,239 horizontal cylindrical holes. A charging machine inserted fresh slugs through the front face of the reactor, and pushed spent slugs out through the rear, where they fell into a water-filled channel. Workers transferred buckets of these irradiated slugs to the neighboring separation plant using an underwater monorail. Exhaust fans pulled cooling air through the pile, keeping it under a slight vacuum to prevent an escape of contamination. Air-cooling was selected for its simplicity, even though engineers had abandoned gas-cooling in favor of water-cooling for the full-scale Hanford reactors in February 1943. Seven feet of concrete shielding protected reactor operators from radiation. Controls included four horizontal "shim" rods, two horizontal regulating rods, six vertical safety rods, and a backup system using boron steel shot suspended over the reactor core. Design-ers provided various openings in the reactor to facilitate the insertion and removal of experimental samples. Initially, X-10 had a power output of 1,000 kilowatts; this output was soon quadrupled.

The X-10 reactor became operational on November 4, 1943. The Clinton Pile focused on plutonium production, research on shielding, and the biological effects of radiation. By February 1944, X-10 was producing several grams of plutonium per month. The high neutron background from this material greatly influenced the design of the plutonium bomb being developed at Los Alamos. X-10 also pro-duced radioactive lanthanum, for use as a tracer in high-explosives experiments, and irradiated bismuth targets to produce polonium-210 for weapon initiators.

After the war, Oak Ridge scientists continued to use the X-10 reactor for reactor research nuclear physics, and isotope production for medical, industrial and agricultural applications. Oak Ridge produced radioactive lanthanum ("Rala") until 1956. The X-10 site became Oak Ridge National Laboratory in 1948. The Oak Ridge Graphite Reactor, as it is known today, was decommissioned in 1963. It is now a national historic landmark, open to visitors.

Hanford 305 Test Pile – To test materials for the full-sized production reactors at Hanford, Manhattan Project engineers used the 305 Test Pile. The reactor's air cooled, natural uranium fueled, 16-foot graphite cube was shielded by five feet of concrete. Horizontal regulating and shim rods controlled the reactor power, with vertical and horizontal safety rods and a steel-shot-filled vertical safety tube in case of emergencies. Uranium metal slugs fueled the reactor, but because of the low power output, they were not designed to be easily removable. Twenty horizontal openings accommodated test stringers for irradiating samples.
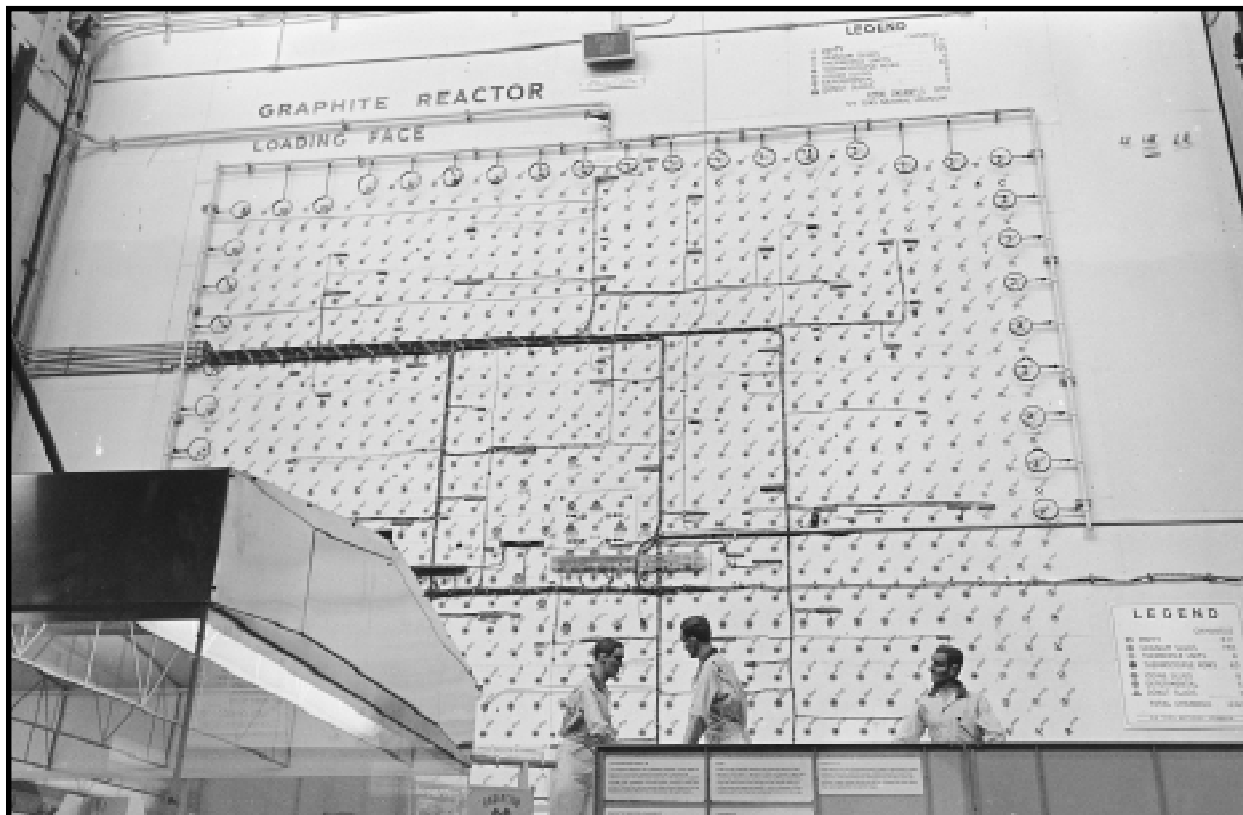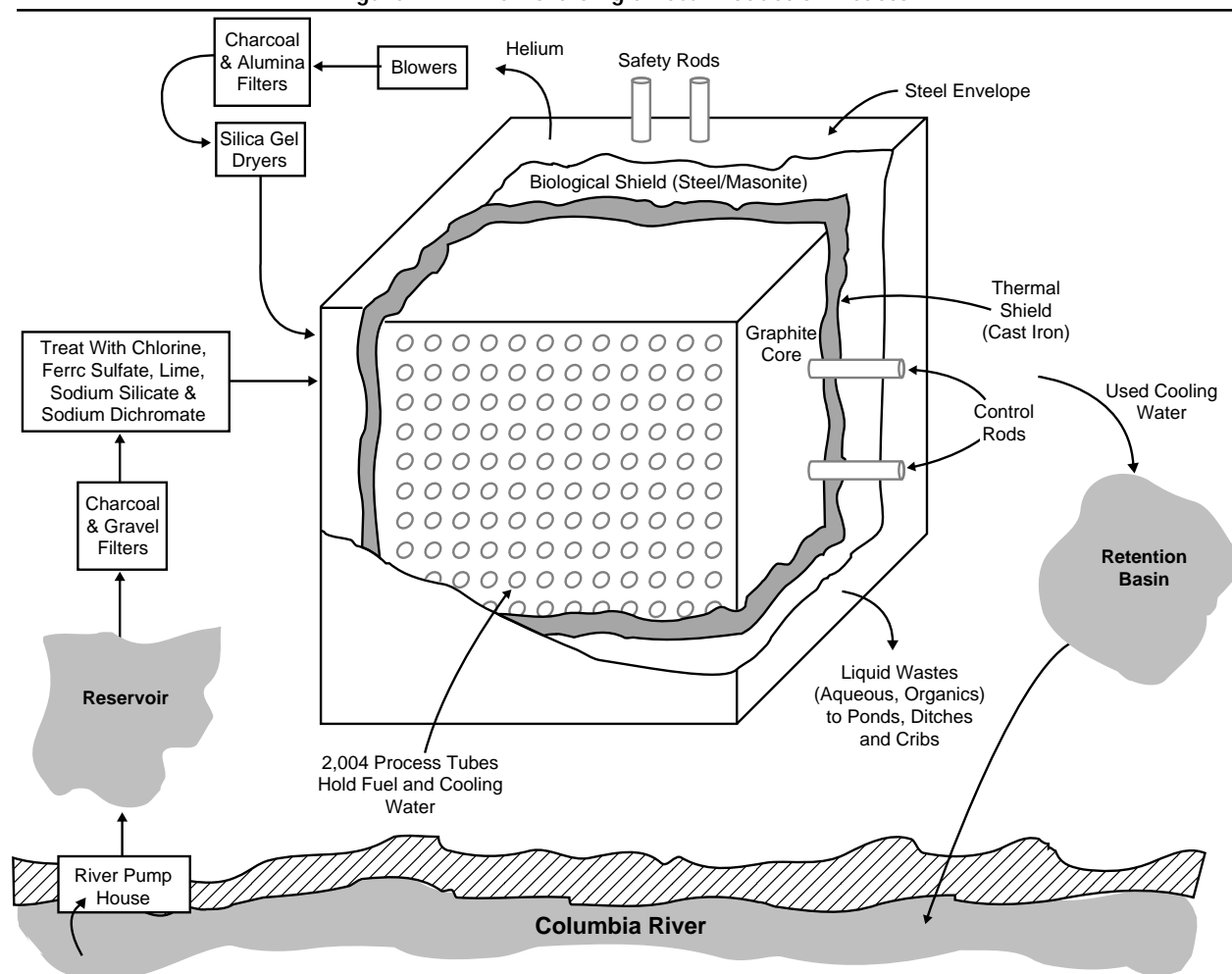
The Oak Ridge Graphite Reactor, code-named "X-10," produced the world's first gram quantities of plutonium. It was the pilot plant for Hanford's full-size plutonium production reactors. X-10's core is a graphite block 24 feet on each side. A charging machine inserted fresh uranium metal slugs through holes in the reactor's front face, pushing irradiated slugs out the back. Fans pulled cooling air over the fuel slugs. Oak Ridge scientists used X-10 for research and isotope production until it was decommissioned in 1963. *Oak Ridge Graphite Reactor Historic Landmark, Oak Ridge National Laboratory, Tennessee. June 11, 1982.*

The 305 reactor began operation at 50 Watts in March 1944 to test graphite, aluminum, uranium and other materials. These tests allowed Hanford engineers to verify that the materials met the strict specifications for use in the three full-scale reactors. The 305 test pile also provided radiation for instrument development. After the war, the 305 Pile tested reactor materials for six more Hanford reactors. The reactor operated through 1972, when the building was converted to fuel fabrication. The 474,000 ton graphite reactor core was dismantled and buried in 1976 and 1977.

Hanford B, D, and F Reactors – MED built three full-scale reactors during World War II to mass produce plutonium for atomic weapons: the B, D and F Reactors. Although originally planned for Oak Ridge, engineers quickly realized that a larger, more isolated site was necessary to protect the public safety. Hanford, Washington was chosen because of its isolation, abundant supply of pure, cold Columbia River water for reactor coolant, and easy access to abundant and reliable hydroelectric power from the Grand Coulee and Bonneville dams.

The core of the Hanford reactors was a block of graphite, 36 by 36 by 28 feet, surrounded by a 10-inch thick layer of cast iron blocks (the "thermal shield") and a laminated masonite and steel biological shield four feet thick to prevent the escape of gamma radiation. The entire block was encased in a welded steel box with expansion joints. The graphite block, built up from over 100,000 graphite bars, contained 2,004 horizontal aluminum "process tubes" to hold fuel slugs and cooling water. The name, "single pass reactors," comes from the fact that cooling water flowed through the reactor and eventually back into the Columbia River. (See Figure B-11).

Figure B-11. Hanford Single-Pass Production Reactor

Charcoal & Alumina Filters

Blowers

Helium

Safety Rods

Steel Envelope

Silica Gel Dryers

Biological Shield (Steel/Masonite)

Thermal Shield (Cast Iron)

Graphite Core

Treat With Chlorine, Ferrc Sulfate, Lime, Sodium Silicate & Sodium Dichromate

Control Rods

Used Cooling Water

Charcoal & Gravel Filters

Retention Basin

Reservoir

Liquid Wastes (Aqueous, Organics) to Ponds, Ditches and Cribs

2,004 Process Tubes Hold Fuel and Cooling Water

River Pump House

Columbia River

Unlike the Clinton pile, the Hanford reactors were gas-tight. A circulating helium atmosphere displaced neutron-absorbing air from the reactor core, and removed gases generated by the reactor. The helium also assisted in the detection of cooling water leaks inside the reactor and helped to dry out the graphite after a leak had been repaired. A separate water cooling system was installed to cool the thermal shield. As in the Clinton pile, DuPont engineers included nine horizontal control rods and 29 vertical safety rods in each Hanford reactor. A backup system would dump a reaction-absorbing boron solution into the safety rod channels. Instrumentation allowed the operators to monitor the reactor power, temperature and other parameters constantly.

Fuel charging and discharging machines inserted slugs into the reactor's front face and removed them from the reactor's rear face. The slugs fell into a pool of water where they were gathered into buckets by remote control to be taken to the separations plants. Dummy slugs made of steel, aluminum or aluminum-canned lead shielded the ends of the process tubes and filled the empty tubes. Engineers devised special machines to replace radioactive process tubes that had become damaged or excessively corroded, and to remove stuck fuel slugs.

Besides the reactor itself, MED built a number of support facilities for each reactor. Key facilities include: the reactor ventilation building; the helium cooling, purification and drying systems; the process water system; and the "lag storage" buildings for spent fuel.

<u>Helium Cooling, Purification and Drying Systems</u> – A blower circulated the helium reactor atmosphere through a filter. Three silica gel dryers removed moisture from the helium as it circulated. Purification of the helium used two activated alumina dryers and four activated charcoal beds. Excess helium vented through an automatic valve. Operators periodically regenerated the charcoal and exhausted the impurities to the plant stack. Despite recycling, the B Reactor consumed 660,000 cubic feet of helium in 1945.

<u>Process Water System</u> – Each of the three wartime Hanford reactors required 30,000 gallons of cooling water per minute at its design power level of 250 megawatts, and each had its own process water system. The reactor areas also "exported" water to the 200 areas and used it locally in boilers and for   other miscellaneous uses. River pump houses drew raw water into a 25 million gallon storage reservoir. Filtered, treated raw water was stored in a 10 million gallon "clearwell." Water from the clearwell flowed into two 1.75 million gallon tanks in the reactor pump house. Deaeration, demineralization and chilling plants were also built, but never used because they proved unnecessary. Chlorine, ferric sulfate, sodium silicate, lime, and sodium dichromate additives controlled the chemistry of the intake water, removed impurities, killed bacteria and algae, and reduced corrosion.

Twelve sets of steam and electric pumps pumped the water through the reactor core. After its passage through the reactor, effluent water flowed into a 12 million gallon retention basin, where radioactivity decayed for a few hours before the water was released back to the Columbia River.

<u>"Lag Storage" Buildings for Spent Fuel Storage</u> – Early Hanford workers called irradiated fuel slugs "lags." The slugs were removed from the reactor discharge basins after about a day and moved the Lag Storage Buildings. Irradiated fuel was initially stored for a few weeks to fifty days to allow fission products (especially iodine 131) to decay before reprocessing to separate the plutonium.

Construction began on B Reactor in June 1943, and start-up occurred in September 1944. D and F reactors were complete and operational by early 1945. The original three Hanford reactors, together with possibly a few grams of plutonium from Oak Ridge, supplied the plutonium for the Trinity test at Alamogordo, New Mexico, on July 16, 1945, and the Fat Man bomb used at Nagasaki, Japan on August 9, 1945.

Post-War Production Reactor Operations

The three Hanford reactors continued to operate through 1945. In 1946, B Reactor was shut down to limit the accumulation of radiation-induced swelling and distortion of its graphite core. After engineers discovered a method of reversing this process, AEC authorized the restart of B Reactor in 1947. Brief shutdowns after this period allowed workers to make many repairs and upgrades to the process water and effluent systems, instrumentation and control systems. The addition of enriched uranium fuel and the "flattening" of the reactor's power distribution using poison slugs and "splines" eventually allowed the World War II reactors' power output to reach over three times their original design levels. However, the increased reactor power caused fuel slug ruptures to begin and increase in frequency, causing increased radionuclide releases to the Columbia River.

Savannah River Site – To increase its plutonium production capacity and provide the large quantities of tritium then believed to be necessary for thermonuclear weapons, AEC selected a new production reactor site on the northern side of the Savannah River separating South Carolina and Georgia. This new site also agreed with AEC's philosophy of maintaining redundant facilities for each weapons production mission. Savannah River Site has five production reactors, code-named R, P, L, K and C. A small sixth reactor in the site's A Area tested materials for constructing the production reactors.

Reactors for the Savannah River Site were designed by DuPont. Unlike Hanford's reactors, the SRS reactors were cooled and moderated with heavy water flowing in a closed loop system at low temperatures and pressures. This arrangement allowed greater efficiency and more flexibility than the graphite reactors at Hanford. Each SRS reactor consisted of a large, shielded stainless steel tank holding 600 fuel and target assemblies. Charging and discharging machines allowed fuel to be loaded and removed from

the reactor by remote control. The reactor's "head" housed 491 movable safety and control rods. A helium gas atmosphere was maintained over the heavy water in each reactor.

Six pumps and circulated the heavy water through 12 heat exchangers at each reactor. Cooling water drawn from the Savannah River removed the heat before being returned to the river via surface streams. Two large artificial lakes at the site, PAR Pond (created in 1958) and L Lake, acted as coolant reservoirs. Backup cooling systems allowed the reactors to be cooled after shutdown in the event of a failure in the main cooling system.

Besides the reactor itself, each SRS production reactor building houses an assembly area, where fresh reactor fuel is stored and assembled; a disassembly area, consisting of a large pool of water where irradiated fuel is stored, disassembled for transport to the chemical separations plants, and loaded into transfer containers; and a purification area, for heavy water treatment and purification. The reactor buildings were equipped with filtered ventilation systems to confine airborne radioactivity.

R, P, L, K, and C Reactors began operating between December 1953 and March 1955. By that time, the tritium requirements for thermo-nuclear weapons had been greatly reduced, and the reactors began

Hot water discharged from the K Reactor at the Savannah River Site flowed through wetlands surrounding Pen Branch stream on its way back to the Savannah River. A cooling tower built in the 1980s eliminated the need to discharge hot water from the K Reactor. However, after the tower was connected to it in 1992, the reactor was never again started up. *K Area, Savannah River Site. January 7, 1994.*

producing plutonium using natural uranium fuel, clad in aluminum. Tritium was produced in the lithium-6 reactor control rods and blankets. Besides plutonium and tritium, the SRS reactors produced cobalt-60, uranium-233, neptunium, plutonium-238 and-242, americium, and curium for nuclear weapons and nonweapons programs.

Between 1961 and 1964, engineers used a small seventh reactor at SRS, the Heavy Water Components Test Reactor, to make these various fuel and target assemblies. The Heavy Water Components Test Reactor shut down in 1965.

In 1968, the SRS reactors were converted to use HEU fuel which increased their output and flexibility, was supplied from four major sources: (1) spent research reactor fuel recovered at SRS H Canyon and ICPP, (2) spent Navy reactor fuel reprocessed at ICPP, (3) SRS production fuel recycled at H Canyon, and (4) weapons-grade HEU (often called Oralloy, Oak Ridge Alloy) from the Y-12 Plant reserves.

SRS conducted a dedicated tritium campaign in 1972, and a second in 1981, in which tritium was produced in specially designed fuel and target elements. After 1981, C Reactor was dedicated to tritium production.

R Reactor shut down permanently in 1964. L Reactor was placed on standby in February 1968, but restarted in October 1985. C reactor stopped operating in 1986, and went on cold standby in 1987, after engineers determined that cracks in the reactor vessel, discovered in 1984, could not be fixed. K, L and P Reactors shut down in 1988 for safety upgrades, and were placed on cold standby. K Reactor restarted briefly in 1989 and 1992.

Hanford H, DR, C, KW, and KE Reactors – AEC further expanded its plutonium production capacity by building five new reactors at Hanford. Beginning in March 1948, AEC built the H, DR, C, KW, and KE production reactors. Their designs were largely identical to the original three Hanford reactors, except that the newer reactors were designed for greater power output. C reactor was built adjacent to B Reactor, and DR (for, "D Replacement,") was adjacent to D reactor. The two K Reactors, also co-located, were known as the "Jumbo" reactors because of their size.

The new reactors were upgraded several times during their operating lives. Zirconium alloy process tubes, less susceptible to corrosion, replaced the original aluminum. As early as 1950, LEU fuel was added to increase power levels, thereby increasing plutonium output. Power increases and safety concerns necessitated improvements to the reactors' coolant systems, fuel slugs, control and safety systems, and instrumentation as well. Carbon dioxide was added to the reactor atmospheres to reduce radiation-induced swelling of their graphite cores. Water treatment changed as well.

Irradiated fuel handling at Hanford changed significantly in 1951. The Lag Storage Buildings did not have enough capacity to accommodate the fuel from the five new reactors being built. The storage buildings were phased out, and fuel began to be stored in the reactor discharge basins. Storage requirements also increased because decay times had been extended to ninety days or more. By the early 1960s, irradiated fuel storage times had increased to between 200 and 250 days.

The Hanford B and H Reactors produced tritium between 1949 and 1952 as part of the P-10 project. Lithium-aluminum slugs were irradiated, with highly-enriched "driver" fuel to sustain the chain reaction. The 108-B Chemical Pump House building became the tritium recovery plant. Tritium was recovered by heating the lithium targets in a vacuum furnace with an inert atmosphere. A palladium valve separated the tritium from other gases. Special pumps transferred tritium gas using mercury to vary pressure levels. The P-10 project ended when AEC transferred the tritium production mission from Hanford to the Savannah River Site in 1952.

All of the original eight Hanford reactors were shut down beginning in 1964 and ending in 1971.[4] Irreversible radiation damage had caused the graphite cores to swell and distort, and the decreasing demand for weapons-grade plutonium was being met adequately by the new Savannah River reactors.

Hanford N Reactor – A ninth Hanford reactor, N Reactor (for "New Production Reactor"), began operating on December 12, 1963. Unlike the original 8 Hanford reactors, N Reactor produced steam used to generate electric power as well as plutonium. N Reactor was LEU fueled, graphite moderated, and water cooled. It used a closed-loop cooling system rather than the single-pass system used in the older reactors.

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[4]   *B Reactor shut down in February 1968; D Reactor, June 1967; F Reactor, June 1965; H Reactor, April 1965; DR Reactor, December 1964; C Reactor, April 1969; K West Reactor, February 1970; K East Reactor, January 1971.*

N Reactor initially produced weapons-grade plutonium from 1964 to 1965. From 1966 to 1973 it produced nine percent fuel-grade plutonium-240 for AEC's breeder reactor program, and from 1974 until 1984, it produced 12 percent fuel-grade plutonium-240. Since the chemical separations plants at Hanford were not operating during most of this period, the irradiated fuel was stored in the K-East and K-West reactor basins. After fuel corrosion became a problem at the K-East basin, water treatment facilities were added to the still-empty K West basin. Then in 1984, N Reactor was converted to produce weapons-grade plutonium (six percent plutonium-240). N Reactor continued to produce weapons-grade plutonium until it was shut down in 1986. The reactor also produced uranium-233 (from thorium-232 targets), small amounts of tritium, and other isotopes.

Beginning in 1981 during a shortage of weapons-grade plutonium and an excess of fuel-grade plutonium, DOE began to blend fuel-grade plutonium from N Reactor with super-grade plutonium (~3% Pu-240) from SRS to make weapons-grade plutonium. All N-Reactor-produced fuel-grade plutonium, except for the amount supplied to and used by the Fast Flux Test Facility (an experimental reactor at Hanford) was considered excess and available for blending. The blending of fuel-grade and super-grade plutonium was performed in F Canyon at SRS. By 1990, all available fuel-grade plutonium had been blended.

Based on the quantity of fuel-grade plutonium used in the blending program, and considering the difference in fuel throughput requirements for weapons and fuel grade plutonium, it is estimated that most of the legacy generated by N Reactor is related to weapons production.

Waste Management for Reactor Operations

Most of the radioactivity in DOE's environmental legacy was created by reactor operations; however, the waste legacy attributed directly to this activity is mostly low-level waste from reactor support operations because the highly radioactive spent fuel and target materials are passed on to chemical separations. Conversely, the volume of legacy of contaminated environmental media and facilities from operation, support and decontamination of the production reactors is very large.

Spent Nuclear Fuel – Spent production reactor fuel and targets are stored at the Hanford and the Savannah River Site. The Hanford fuel was accumulated in the 1970s and early 1980s when the N Reactor was operating but the PUREX plant was shut down. Over 100,000 N reactor fuel assemblies and a much smaller number of single-pass reactor fuel slugs are stored in the K-East and K-West basins. DOE plans to move these materials into dry storage in a new facility away from the banks of the Columbia River.

Savannah River Site has stored thousands of irradiated targets in the K, L and P Reactor disassembly basins for several years after the shutdown of its production reactors. To stabilize the corroding materials, SRS dissolved and processed these targets in 1996. Spent fuel from SRS, containing highly-enriched uranium, continues to be stored in the reactor disassembly basins. These materials will also be dissolved and reprocessed, beginning in late 1996.

Spent nuclear fuel from Naval propulsion reactors, research and test reactors and some commercial nuclear power plants is stored at the Idaho National Engineering Laboratory, the Y-12 Plant, Argonne National Laboratory-East, Argonne National Laboratory-West, Brookhaven National Laboratory, Sandia National Laboratory, Los Alamos National Laboratory, the Fort St. Vrian Reactor in Colorado, and the West Valley Demonstration Project in New York. U.S. origin irradiated fuel is also being returned to the United States by the operators of research reactors in other countries. DOE plans to consolidate these materials based on their cladding type at the INEL and Savannah River.

Reactor Coolant Discharges – The eight single-pass reactors at Hanford discharged coolant to the Columbia River after a few hours' delay in a retention basin. This reactor effluent was radioactive because of activation of dissolved minerals and water treatment chemicals, and entrainment of corrosion products from the surfaces of the reactor fuel and process tubes. Fuel slug ruptures also released radioactivity into the coolant. Periodic "purges" using diatomaceous earth slurry to remove deposits on the surfaces of the process tubes also contributed to the releases. Radioactivity from these discharges was detected in

sediments and fish at the mouth of the river, several hundred miles away. Engineers considered building an inland lake system to increase the delay in releasing radioactive effluent to the river, but the idea was rejected because of concerns with environmental contamination. Conversion to closed-loop cooling systems was determined to be too expensive. Effluent decontamination was successfully demonstrated but proved to be impractical. Water treatment changes were more successful in reducing radionuclide releases to the river.

Besides radioactive contaminants, the Hanford reactor effluents contained hexavalent chromium, a toxic heavy metal used to reduce corrosion of the reactor's aluminum process tubes. Reactor discharges also raised the temperature of the river water, although Hanford workers installed structures to encourage mixing.

Leaks in the effluent retention basins at Hanford allowed contaminants to reach the groundwater beneath the reactor areas. Reactor operators diverted unusually radioactive effluents from slug ruptures or reactor purges to cribs, where it was believed that the radioactive water would be held in the pores of the soil.

At the Savannah River Site, releases of radioactive coolant were not routine because of the reactors' closed-loop cooling systems. However, heat exchanger leaks, reactor purges and other discharges allowed radioactive water to escape the reactors many times. In addition to the activation of native elements, water treatment additives, corrosion products, and fission products released by failed fuel elements, the heavy water in the Savannah River Site reactors contained significant amounts of tritium, which built up as the reactors operated.

During its first years of operation, the Savannah River Site released reactor cooling water and disassembly basin effluents directly to Steel Creek, Lower Three Mile Runs Creek, and the Pen Branch stream. To allow the reactor effluent to cool before leaving the site, engineers created PAR Pond in 1958, and L Lake in 1961, by damming Steel Creek and Lower Three Mile Runs Creek. K Reactor continued to discharge its cooling water directly to Pens Branch. Heat from reactor effluents affected plant and animal life on the site. SRS built a cooling tower in the late 1980s to replace the surface water discharge, and mitigate the effects of the hot water discharge. However, the reactor was not operated after it was connected to the new facility.

Sediments in PAR Pond at the site are contaminated with cesium-137 and transuranics as a result of reactor discharges in the late 1950s and early 1960s. Elevated levels of mercury have also accumulated in the sediments. The mercury came from water pumped from the Savannah River to keep the reservoir full.

Other Liquid Wastes from Reactor Operations – Reactor operations generated many liquid wastes in addition to large amounts of reactor coolant. These wastes included contaminated discharge and disassembly basin water, lubricating oils, solvents and acid solutions used to clean and decontaminate reactor equipment, and laboratory wastes. Operators disposed of contaminated water from water-fog systems used to decontaminate reactor gases at Hanford in soil cribs. Leaks and spills involving paint, gasoline, diesel fuel, water treatment chemicals and other substances also contributed to contamination in the reactor areas at both reactor sites. A total of 21 cribs and 19 ponds and ditches received waste from the Hanford reactor areas. Mercury from the pumps used to handle tritium in the B Area was regularly disposed to the soil.

Water from the fuel storage and disassembly basins at SRS contains tritium and other radionuclides that adhered to the fuel elements when they were removed from the reactor. In 1957, seepage basins began to receive low-level radioactive water from the fuel disassembly basins. These basins were intended to delay the migration of tritium into the surface streams and to allow other radionuclides to remain in the soil. Six seepage basins received effluent from R Reactor. Engineers closed the first basin in 1958 after it received an unusually radioactive discharge. The other basins were closed and backfilled between 1960

and 1964. A single basin at K Reactor closed in 1960. The site replaced its seepage basins with containment basins.

Atmospheric Releases of Radioactivity from Reactor Operations – Reactor operations generate radioactive gases through activation of gases in the reactor, radiolysis (radiation-induced breakdown) of graphite, water and other reactor materials, and fission products escaping from failed fuel and target elements.

Gases generated in the Hanford reactors exhausted directly to the atmosphere. The reactor exhaust included noble gases generated in the fission process (radioactive krypton-85, xenon-133 and argon-39, -41 and -42), halogen gases (iodine-131 and bromine-82), and particulates and aerosols containing cesium -137, tellurium-129, selenium-79, ruthenium-103/-106 and other radioactive elements. Water-fog installed at the Hanford reactors in the late 1950s and late 1960s removed most of the radionuclides, the exception being the noble gases.

Solid Wastes Generated by Reactor Operations – Reactor operations generated considerable solid wastes. Worn out, excessively contaminated, or obsolete reactor and support system components were replaced as needed and buried. These included air filters, instruments, fuel transport casks and handling equipment, "dummy" slugs, poison splines, silica gel for gas purification, process tubes, coolant headers and piping, in-reactor instruments, gaskets, and seals. Contaminated clothing, shoe covers, wipes, etc., used by maintenance workers and operators were also regularly buried. Hanford reactor operators buried most of their wastes in the reactor areas, while SRS buried its solid wastes at a central burial ground.

Nonradioactive solid wastes from reactor operations included activated charcoal and other filter media, water softening resins, and fly ash from steam plant boilers.

CHEMICAL SEPARATIONS

The T Plant was the world's first reprocessing canyon. In 1944, it disolved spent fuel from the Hanford B Reactor and chemically extracted the plutonium, which was then used to form the core of the Trinity and Nagasaki bombs. It continued reprocessing until 1956. Today the plant is used to decontaminate equipment. *Hanford Site, Washington. July 11, 1994.*

Chemical separation is the process of chemically separating and purifying plutonium, uranium and other nuclear materials from irradiated reactor fuel and targets, and converting the materials to usable forms. The process includes: physical disassembly and chemical dissolution of irradiated items; separation of uranium, plutonium and fission products; decontamination or purification; volume reduction or concentration; and isolation. Operations considered as first stage finishing processes are also included, e.g. the precipitation of heavy metal nitrate solution mixtures, hydro-fluorination, and metal reduction.

Chemical separation of spent fuel and target elements produces large volumes of highly-radioactive, high-level waste (HLW), low-level waste (LLW) and mixed low-level waste (MLLW). Chemical separation of plutonium and other transuranic isotopes also results in transuranic waste (TRUW). Contaminated environmental media and facilities from chemical separations of irradiated reactor materials pose unusual and severe restoration problems.

**Manhattan Project Chemical Separation**

A chemical process was required to separate plutonium to be used in the first atomic bombs from irradiated uranium reactor fuel. The lack of actual irradiated uranium for experimentation, ignorance of the chemical properties of plutonium, and engineering inexperience with high radiation levels, complicated the development effort tremendously. The Metallurgical Laboratory at the University of Chicago was responsible for developing the separations processes and did develop a number of candidate processes. DuPont was chosen to build the plant and on June 8, DuPont engineers in Wilmington, Delaware chose

171

Figure B-12. Bismuth Phosphate Chemical Separation at Hanford
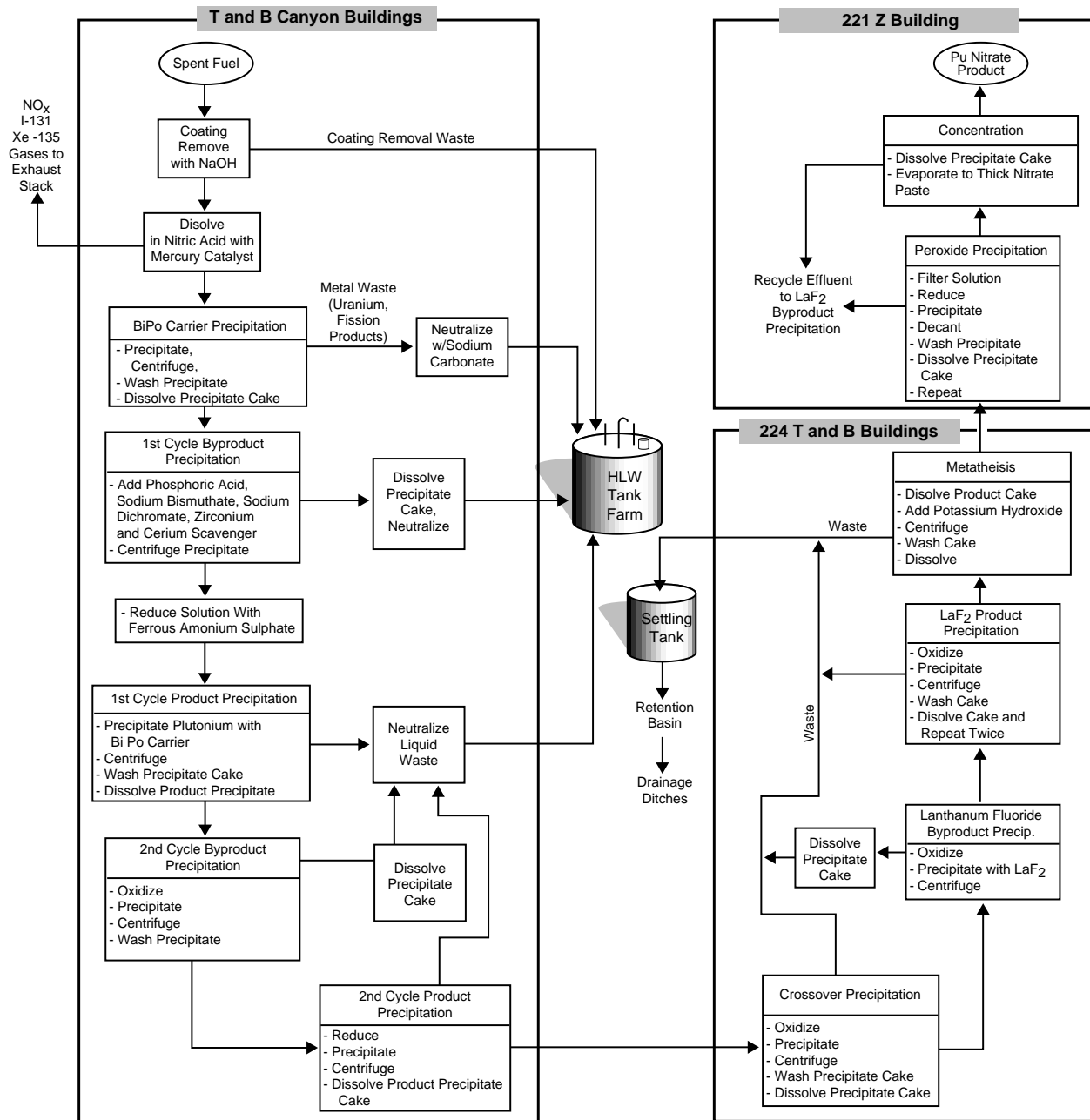
Note: *The bismuth phosphate process separated and purified plutonium through successive cycles of precipitation and dissolution using bismuth phosphate as a carrier. Bismuth phosphate was dissolved along with the irradiated uranium. Changing the chemistry of the solution caused bismuth phosphate to solidify into a fine, powdery precipitate. In each byproduct precipitation, wastes and impurities were solidified with the bismuth phosphate while the plutonium remained dissolved. The waste precipitate was removed from the solution in a centrifuge. The cake of solid waste left in the centrifuge was dissolved and transferred to the waste tanks, while the liquid went on to the next step. Following each byproduct precipitation was a product precipitation. Changing the chemistry of the solution allowed plutonium to be carried out of the solution with the bismuth phosphate precipitate, so that it could be separated from impurities that were not removed with the bismuth phosphate. After centrifuging out the waste liquid, the cake of bismuth phosphate and plutonium was redissolved and sent on for further purification and concentration. Lanthanum flouride replaced bismuth phosphate in the final concentration and purification, using a similar process.*

Figure B-13. **PUREX Reprocessing**
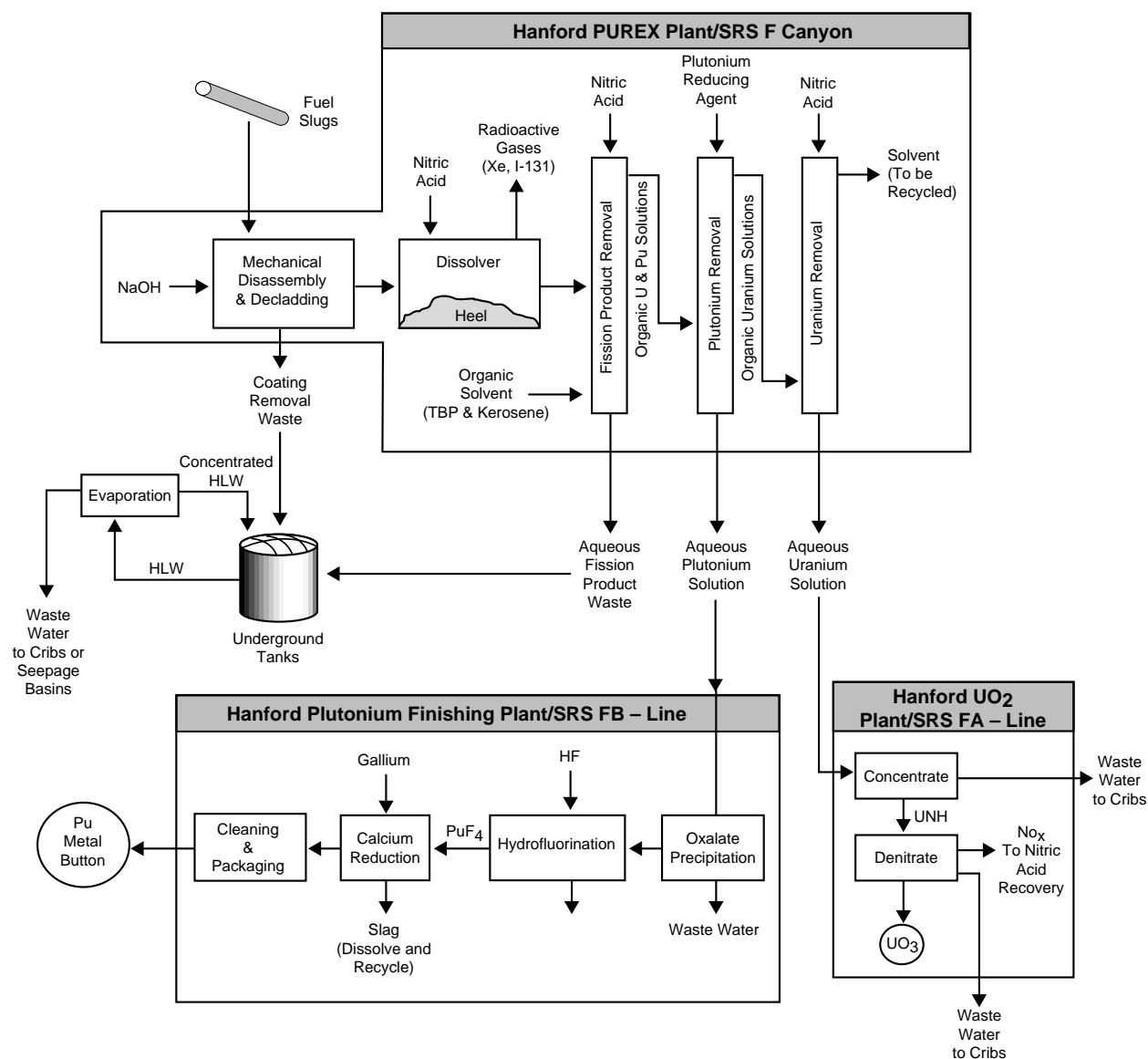
the bismuth phosphate process for the full-scale plants. To save time, construction of the separation plants began even before the process had been selected.

The X-10 Pilot Plant – The bismuth phosphate process was demonstrated on an engineering scale in a pilot plant alongside the X-10 Reactor located in Oak Ridge, Tennessee. The first irradiated uranium from the X-10 reactor was dissolved on December 19, 1943. Beginning in February 1944, X-10 produced several grams of plutonium per month. These first samples of plutonium allowed scientists at Los Alamos to determine the new metal's chemical, metallurgical and nuclear properties. Their unexpectedly high spontaneous fission rate greatly influenced the design of the plutonium fueled atomic bombs.

Hanford T, B and U Plants – Drawing on the experience with the pilot plant in Oak Ridge, MED built the T, B, and U Plants at Hanford which used the bismuth phosphate process. The T and B Plant "canyons" produced a plutonium nitrate solution. This product was sent to the 224-T and 224-B Bulk Reduction

Plants to be further decontaminated and concentrated from 330 gallons down to eight gallons using a lanthanum fluoride carrier process. The concentrated solution from these plants was in turn taken to the 231-Z Building to be made into the Hanford Site's final product, a wet plutonium nitrate paste. See the text box, "Chemical Separations Processes" and Figure B-12 for an explanation of the separation process used in T and B plants. U Plant and its associated facilities were used only for training and as a backup because the T and B Plants had sufficient processing capacity.

The T and B Plants each consisted of a main building over 800 foot long. T Plant was 65 feet longer than B and U Plants to allow extra space for experiments. Workers at the site called these buildings "canyons," or "Queen Marys," because of their shape: they were 102 feet high and 85 feet wide. Thick concrete walls provided shielding from the intense radioactivity. The plants were divided into 20 cells (22 in T Plant) with removable covers. Overhead cranes and remote manipulators allowed equipment to be replaced remotely. The equipment itself was designed for remote handling and replacement. Galleries for electrical and control equipment, pipes, and operators ran the length of the buildings. Closed-circuit television allowed workers to see inside the canyons. A ventilation system drew air into the occupied areas, then through the contaminated areas before it exhausted through filters and a tall stack. The 224 T, B and U buildings and the 231 Z Isolation Plant were also made of reinforced concrete with special ventilation systems.

The T Plant, the first full-scale Manhattan Project era separations plant, began operating in December 1944, while the B Plant started operating in April 1945. The plants sent approximately 10,000 gallons of waste to the tank farms for every metric ton of uranium fuel they processed. T and B Plants also discharged approximately 1.5 million gallons of wastewater into the ground each day.

B Plant shut down in October 1952, and T Plant shut down in March 1956. Over 7,000 metric tons of irradiated production fuel were processed using bismuth phosphate in these facilities. T Plant began to be used as a decontamination facility after its chemical separation mission ended, becoming Hanford's central decontamination plant in 1958. Workers at T Plant used steam, sandblasters, chemical solvents, and detergents to decontaminate equipment. B Plant was later used to recover and encapsulate cesium 137 and strontium-90 from the HLW tanks to make radiation sources.

231-Z Plant (Hanford) – The 231-Z Plant (also known as the Isolation Plant) received concentrated plutonium nitrate from the 224-T and 224-U Buildings. In 231-Z, hydrogen peroxide, sulfates, and ammonium nitrate were added and the plutonium was precipitated out of the solution as plutonium peroxide. The peroxide was filtered, dried, dissolved in nitric acid, and boiled down to a thick, wet paste. The plutonium nitrate paste was shipped to Los Alamos. Z Plant started processing plutonium in 1945.

Post-War Expansion of Chemical Separation at Hanford

Plutonium Finishing Plant (Hanford) – The Plutonium Finishing Plant (234 Building, PFP) was built in 1948 and began processing plutonium in July 1949. When the Plutonium Finishing Plant began converting plutonium nitrate to metallic plutonium in 1949, Z Plant stopped shipping its product to Los Alamos. The plutonium metal "buttons" were made into nuclear weapon "pits" at PFP (1949-1965) or the Rocky Flats Plant (1952-1989). Besides weapons plutonium, PFP also processed fuel grade plutonium beginning in 1964. Processing of nondefense, fuel grade plutonium occupied approximately 30 percent of the plant's capacity in the late 1960s, and defense plutonium production ceased in 1973. PFP was restarted in 1984 and processed defense plutonium again until June 1989.

PFP received plutonium nitrate paste from 231-Z and converted it into metal in a three step process. First, the nitrate was diluted and oxalic acid was added to precipitate plutonium oxalate. The oxalate was then filtered and dried. Next, hot hydrogen fluoride gas was mixed with the oxalate to form plutonium tetrafluoride (PuF_4, also called "pink cake"). Finally, the tetrafluoride and a small amount of gallium were mixed with calcium metal and heated until the reactants ignited. The products of this reduction process are plutonium metal "buttons" and calcium fluoride.

REDOX Plant – The Bismuth Phosphate process, while effective, was inefficient, processing only 1 to 1.5 tons of fuel per day. A new process, called REDOX, was developed beginning in 1947 in the 3706 Building and tested in the 321 Building in Hanford's 300 Area. REDOX was the first continuous-flow solvent extraction process designed for nuclear fuel reprocessing, and it was the first process to recover uranium as well as plutonium. See the text box "Chemical Separations Processes" for an explanation of the REDOX process.

Construction of the REDOX Plant, also known as S Plant, at Hanford began in 1949 enhanced in late 1951. REDOX plant, although large and heavily shielded, was not a "canyon" shaped building like the bismuth phosphate plants. Designed to process up to 3 tons of fuel per day, the plant's capacity increased to 8 tons per day by 1954 and reached 12 tons per day in 1958. Part of this capacity increase was due to the construction of the 233-S Plutonium Concentration Building, where criticality-safe equipment accomplished the third and final plutonium concentration step. Plutonium solutions from REDOX were sent to the 231-Z Plant for reduction to metallic plutonium. The uranyl nitrate hexahydrate product solution from REDOX was solidified in the UO_3 Plant and shipped to Oak Ridge to be recycled as feed for the uranium enrichment plants. Besides plutonium and uranium, REDOX recovered neptunium-237.

The REDOX plant shut down in December 1967. During its operation, the REDOX Plant processed over 19,000 metric tons of spent fuel.

Development of the PUREX Process

REDOX, while an improvement over the bismuth phosphate process, was less than ideal. To increase efficiency and reduce operating costs, a new separations process, called PUREX, was developed. PUREX was developed by Knolls Atomic Power Laboratory in the early 1950s, and demonstrated at the Knolls Laboratory's Separations Process Research Unit in Schenectady, New York. The process was first used at the Savannah River Site and later adopted at Hanford and the Idaho Chemical Processing Plant.

F and H Canyons (Savannah River Site) – To recover plutonium from the Savannah River Site's five reactors, AEC built two chemical separation plants: one in the F Area, and one in the H Area. Savannah River Site's chemical processing plants were the first to use the PUREX process on a large scale. Large-scale chemical separation operations at F Canyon began at SRS in November 1954 and H Canyon started processing irradiated reactor fuel in July 1955. The F and H area separations plants initially

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Chemical Separations Processes

Three basic chemical separations processes have been used on a production scale in the United States and have produced the bulk of the DOE HLW: the bismuth phosphate process, the REDuction OXidation (REDOX) process, and the Plutonium URanium EXtraction (PUREX) process.

Bismuth Phosphate Process – This batch process is based on the fact that plutonium will co-precipitate with bismuth phosphate in the +4 valence state, but not in the +6 valence state. Aluminum cladding was dissolved away from the fuel elements using boiling sodium hydroxide solution. The bare uranium was then dissolved in concentrated aqueous nitric acid and plutonium was separated and concentrated by many cycles of precipitation and dissolution using bismuth phosphate. The bismuth phosphate process could only extract plutonium; the uranium remained in the high-level waste stream. See Figure B-12 for a schematic of the process.

REDOX Process – The REDOX process was the first countercurrent, continuous-flow process for recovery of both plutonium and uranium. The heavy radionuclides (plutonium and uranium) and fission products were separated in two liquid streams—an organic solution and an aqueous solution—which are not soluble in one another. REDOX began by decladding and dissolution of spent fuel and targets in nitric acid. An organic solvent is mixed with the resulting aqueous solution and the uranium and plutonium nitrates are transferred into the organic solvent; the fission products remain and are removed in the aqueous phase. Uranium and plutonium nitrate were then each separately reduced chemically and removed in the aqueous phase.

PUREX Process – The PUREX process is capable of recovering plutonium, uranium, and other materials in separate cycles by countercurrent flow with organic solvents. The process begins with dissolution of the irradiated material in nitric acid. An organic solvent is introduced and the uranium and plutonium nitrates transfer into the organic solvent while the fission products remain and are removed in the aqueous phase. The desired materials—plutonium, uranium, and sometimes others, notably neptunium—are extracted and concentrated together in an organic solvent and then purified by chemical scrubbing with dilute nitric acid. Two further cycles of solvent extraction and scrubbing each result in separate, concentrated, and purified aqueous solutions of plutonium nitrate and uranium nitrate. When other materials are extracted, additional cycles of the nitrate solution are required. See Figure B-13 for a schematic of the process.

F Canyon Control Room. From this room, operators controlled the processing of irradiated reactor targets. The targets were dissolved in acid so that plutonium could be separated from the uranium and highly radioactive fission product wastes. *F Area, Savannah River Site, South Carolina. January 6, 1994.*

processed the irradiated NU fuel from the five SRS reactors. The F Canyon area included the FA Line facility to solidify recovered uranium. Recovered uranyl nitrate solution from the H Canyon was brought to the F Area by truck.

After SRS reactors converted to HEU fuel and separate DU targets in 1968, F Canyon, and FB Line on the 6th and 7th levels of F Canyon were the primary facilities for recovering and finishing weapons-grade plutonium from the targets. F Canyon received irradiated DU target elements from the reactors and separated and purified the plutonium nitrate. FB Line solidified the plutonium nitrate solutions to a plutonium oxide powder or metal to be machined into weapon components at the Rocky Flats Plant (RFP). A byproduct of the process was DU in the form of UO_3, some of which was solidified in the FA Line and sent to FMPC to be recycled into more targets. However, more than 35,000 55-gallon drums of excess UO_3 accumulated at SRS.

After 1968, the H Canyon and HB Line facilities recovered HEU nitrate from spent SRS production reactor fuel and some research reactor fuels. H Canyon, HB Line, and the other 200H Area facilities were also used for separation and purification of tritium, neptunium, plutonium-238, americium, curium, and other elements and isotopes. The recovered HEU was shipped to the Y-12 Plant in Oak Ridge for reduction to metal to supplement the HEU stockpile or to be reused as SRS production reactor fuel.

H Canyon and F Canyon also recovered neptunium 237 to be used as targets for the production of plutonium-238. H Canyon recovered plutonium-238 from irradiated neptunium for use in power sources for deep space probes, and sometimes other exotic isotopes for nuclear weapons, civilian research, and medical uses.

These stainless steel canisters, weighing 1,100 pounds each, are engineered to contain vitrified high-level waste for long-term storage and disposal. When full, the canisters weigh 3,700 pounds each and they are extremely radioactive. Although a long- term storage site is not yet available, solidifying the waste greatly reduces the risk of storing it. Eighty-seven canisters have been filled with vitrified high-level waste as of December, 1996. A total of over 5,500 are planned to be filled during the next 25 years. *Defense Waste Processing Facility, S Area, Savannah River Site, South Carolina. June 15, 1993.*

AEC originally developed the Savannah River Site to produce tritium. Although advances in weapons design greatly reduced the need for tritium by the time the site began to produce it, SRS has been the Unites States' primary tritium production facility since the mid-1950s.

The original SRS tritium processing facility, located in Building 232 -F, began extracting tritium from lithium-6 aluminum target elements irradiated in the five SRS production reactors in 1955. However, in 1958, it was replaced by a new facility located in the 230-H series of buildings in H Area. The original 1955 facility sat idle until it was decommissioned between 1994 and 1996. Although SRS has not produced new tritium since the last production reactor was shut down, a new facility called the Replacement Tritium Facility (RTF) began operating in 1993. RFT currently reloads tritium reservoirs for the nuclear weapons stockpile. DOE's current plans call for this facility to be expanded to process new tritium produced in either a linear accelerator at SRS or commercial nuclear power plants.

Idaho Chemical Processing Plant – The Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering Laboratory (INEL, called the National Reactor Testing Station at that time) began to process spent Navy, research, and experimental reactor fuel in 1953 to recover and recycle HEU. ICPP used a variant of the PUREX process that was not designed to recover plutonium. The recovered highly-enriched UO_3 was shipped as a solid powder to the Y-12 Plant where it was reduced to metal and became a supplemental source of fuel for the SRS production reactors after they converted to HEU fuel in 1968. Later modifications allowed ICPP to recover radioactive xenon and krypton gases for industrial uses.

Because of the wide variety of fuels processed at ICPP, the plant operated on a custom campaign basis, using a variety of "head end" processes to declad and dissolve different types of reactor fuels. For example, the ROVER facility was built from 1983 through 1985 and used to recover HEU from carbon-

coated uranium carbide particles in a graphite matrix used as fuel for the experimental ROVER nuclear rocket program of the 1960s. Another new "head end" dissolving facility, the Fluorinel Dissolution Process, was built in the mid-1980s.

Construction of a new fuel processing facility at ICPP began in 1987, but was never completed. ICPP shut down in 1992. Spent fuel from many research, test and Naval reactors, along with fuel from several commercial reactors and debris from the Three Mile Island accident, is stored in pools and dry casks at the ICPP.

PUREX Plant (Hanford) – The PUREX Plant, also known as A Plant, at Hanford became operational in January 1956. It received irradiated LEU fuel from the Hanford reactors. The plant was modified in 1963 to process the zirconium-clad fuel from the N Reactor. The products of the Hanford PUREX Plant were pure plutonium nitrate, LEU nitrate, and sometimes other materials, including neptunium-237. The PUREX plant also processed irradiated thorium oxide fuel to recover uranium-233 in 1965, 1966, and 1970.

PUREX shut down in June 1972 for cleanout and upgrades and to allow the accumulation of irradiated fuel. Upgrades for waste management, seismic safety and other reasons delayed the restart of the PUREX plant until November 1983. After the restart, PUREX shipped plutonium to the Plutonium Finishing Plant as an oxide (PuO_2, also known as "green cake") rather than a liquid nitrate solution. For a few months in 1984, the restarted PUREX plant sent PuO_2 to TA-55 at Los Alamos instead, because of an accident at PFP. The PUREX plant closed for six weeks in 1988, and then for the entire year of 1989. PUREX operated for the last time for a short cleanout run in 1990, and the Department decided to close it permanently in 1992.

U Plant (Hanford) – Uranium was scarce in the 1940s and early 1950s. The bismouth phosphate process did not recover uranium from the irradiated fuel processed at Hanford. As a result, a significant portion of the uranium resources in the world was stored in the Hanford tanks. Some of this uranium was enriched, making it even more valuable. The U Plant at Hanford, which was built as a chemical separation plant in 1945 but never operated, was retrofitted to use a variant of the PUREX process to recover and recycle uranium from the HLW storage tanks at Hanford. Also known as the TBP Plant and the Metal Recovery Plant, the U Plant began this mission in 1952 and continued it until 1958.

UO_3 Plant (Hanford) – The UO_3 Plant was a major modification of the original, unused 224-U Bulk Reduction Building that began its operations in 1953. This plant solidified uranyl nitrate hexahydrate from the REDOX and PUREX separations plants and the U Plant, which recovered uranium from the high-level waste tanks. The UO_3 plant was shut down during the summer of 1955 for a major expansion, the 224-UA building, and the building resumed service in 1956. The UO_3 plant was again shut down in 1972, at the same time as the PUREX plant, and was restarted in 1984, shortly after the PUREX plant. Because its capacity to solidify UNH from processing of N Reactor fuel exceeded that of the PUREX plant to generate it, UO_3 plant operated as needed, with 17 startups and shutdowns, until April 1993. UO_3 Plant's product was shipped by rail to Oak Ridge to be converted into UF_6 to feed the gaseous diffusion plants.

Chemical Separation Waste Management

Chemical separation process wastes include the "cladding wastes" produced by the removal of the coating from irradiated fuel elements, and the high-level wastes containing the fission products separated from the uranium and plutonium. Miscellaneous low-level and transuranic waste streams came from plutonium concentration and finishing processes, uranium solidification, floor drains, laboratory analysis, and other activities.

T and B Plant Wastes – Hanford categorized bismuth phosphate process wastes as coating removal waste, first- and second-cycle decontamination wastes, and cell drainage waste. The first three waste types were neutralized with sodium hydroxide and stored in 16 underground tanks. Each tank was made of reinforced concrete lined with a quarter inch of steel plate. Twelve of the tanks were 75 feet in diameter, and

These single-shell tanks stored high-level radioactive wastes from Hanford's chemical separations plants. The tank farm shown here was built for the Manhattan project during World War II to hold wastes from the T Plant, which separated plutonium from irradiated reactor fuel. *200 Area, Hanford Site, Washington. Mid-1944.*

four were 20 feet across. The fourth waste stream was discharged to the ground. Wastes from the 224 buildings were stored in a 20 foot diameter settling tank, then combined with used cooling water and discharged to retention basins (two for each plant) and then into drainage ditches.

Hanford constructed additional single-shelled tanks in the late 1940s and early 1950s. To preserve HLW tank space, evaporators in the T and B Plant areas removed water (containing low levels of radioactivity) from the first cycle decontamination wastes and discharged it to the ground. At the same time, wastes from the 224 buildings, second-cycle decontamination, and coating removal (including those already stored in tanks) began to be sent to holding tanks. The supernate from these wastes was discharged to the ground. Several experiments in the 1950s tested the discharge of high-level waste to retention trenches and cribs. Many spills and leaks, some quite large, also released high-level wastes to the environment.

Radioactive air emissions from chemical separation were a continuing problem as well. Xenon and iodine gases emitted as the irradiated fuel slugs dissolved were released through the plants' ventilation stacks. Beginning in the fall of 1947, emissions of radioactive particulates and mists from the stacks appeared. Workers installed scrubbers and sand and fiberglass filters to reduce these emissions. Iodine emissions continued to be a problem, although they were lessened by an increase in fuel cooling times to between 90 and 125 days. (In 1945, fuel storage times were as short as 30 days.) Silver iodide filters installed in 1950 removed most of the iodine from the stack gases. Mercury, silver, potassium and sodium added to the dissolver also reduced the generation of iodine gas by keeping the material dissolved in the waste.

Hanford – The REDOX and PUREX plant wastes differed from those generated by the bismuth phosphate process. High-level wastes continued to be stored in single shelled tanks. Tanks containing REDOX plant wastes generated enough radioactive decay heat to boil. In 1952 and 1953, cooling coils inside these self-boiling tanks ruptured, allowing the high-level wastes to escape through the cooling system. Newer tanks were equipped with mixers to prevent these ruptures. Vapor generated by the hot tank wastes was exhausted to the atmosphere through filters.

During its uranium recovery process, the U Plant added ferrocyanides to its wastes to remove cesium -137. While these additions allowed greater amounts of waste to be discharged to the ground, conserving tank space, the ferrocyanides in the waste returned to the tanks have greatly complicated HLW management at Hanford.

A modified B Plant began to remove cesium and strontium from the HLW tanks at Hanford in 1968. Hanford continued this waste partitioning mission until 1983. B Plant initially stored the cesium and strontium capsules, but they were transferred to the Waste Examination and Storage Facility (WESF), an addition to B Plant, in 1971. DOE and its predecessors leased many of the capsules as intense radiation sources for industrial uses. However, the capsules deteriorated over time, and the WESF accepted the last returned capsule in 1996.

Corrosion eventually caused leaks in single-shelled tanks. Sixty-six leaks, totalling one million gallons, are known to have occurred at Hanford. The last of these tanks was built in 1964, after which double-shelled tanks, which are more resistant to leaks, became the standard. Hanford has a total of 177 HLW tanks, including 149 with single steel shells.

Ground disposal of low-level and transuranic liquid wastes continued after the war. A total of 100 cribs, 45 specific retention trenches, 55 ponds and ditches, 9 injection wells and 29 french drains received wastes from the chemical separations plants at Hanford. Liquid transuranic waste was discharged until 1973, and low-level waste discharges continued until 1994. Although the organic solvents used in the separations processes were recycled, they eventually degraded and were disposed into soil cribs. Other crib wastes included laboratory wastes, floor drain wastes, acid fractionator wastes, process and steam condensate, and condenser cooling water.

Two hundred and five spills and leaks have occurred at the Hanford chemical separations areas since 1944. Most of these releases were small, but some were quite large.

Hanford's 100 Area discharged an estimated 350 billion gallons of wastewater into the ground between 1945 and 1991. The PUREX plant alone discharged up to 10 million gallons of water each day. While waste generation per unit of dissolved heavy metal fell by a factor of 100 between 1945 and 1960, the output of irradiated fuel increased considerably. Groundwater mounds formed beneath the Hanford chemical separation areas as a result of the large amounts of liquid waste discharged to the ground. These mounds caused the flow of contaminated groundwater toward the Columbia River to accelerate and change direction. Engineers relocated ground discharges in an attempt to control the flow of contaminated groundwater. Solid wastes from Hanford chemical separations are also buried at the 200 Area.

The Savannah River Site – Fifty-one underground carbon steel tanks, encased in concrete vaults, store high-level radioactive wastes at the Savannah River Site. There are four different types of HLW tanks at the site. Twenty-four of these tanks are single-walled, with a catch pan to contain leaks. The remaining twenty-seven tanks are double-walled.

To preserve tank space, engineers at Savannah River reduced the 83 million gallons of high-level waste produced at the site to 34 million gallons by evaporation of liquids. Evaporation began at F Area in 1960, and H Area in 1963. The high level waste was initially stored in a settling tank, where solids settle to the bottom. The resultant clear liquid (supernate) was concentrated by evaporation. Evaporator water, containing low levels of radioactivity, was discharged to the F and H Area seepage basins. Since 1990, the

evaporator water has been rerouted to the Z Area Saltstone facility, where it is mixed with concrete and stored in aboveground vaults.

The Defense Waste Processing Facility (DWPF), which DOE began to build in 1983, started processing HLW at SRS into glass logs in 1996. DOE has constructed an In-Tank Precipitation facility to pretreat the tank wastes before they are vitrified in the DWPF.

Hazardous and low-level radioactive liquid wastes from chemical separation at the Savannah River Site were also discharged to the F and H Area seepage basins between 1954 and 1988. After evaporation, some wastes were released to local streams. After 1988, the F and H Area Effluent Treatment Facility received these wastes, including process wastewater, contaminated canyon cooling water, and tank farm runoff. The Effluent Treatment Facility discharges the treated water to Upper Three Runs Creek.

Waste from the semi-works facility and laboratory in the TNX area was also disposed in seepage basins. The Old TNX Seepage Basin received wastes between 1958 and 1980, and the new TNX Basin operated from 1980 until 1988 when it was replaced by the Effluent Treatment Facility. Four more seepage basins were used at the Savannah River Technology Center from 1954 until 1982.

E Area Radioactive Waste Burial Grounds at SRS segregated and buried solid hazardous, low-level and transuranic waste in shallow unlined trenches between 1952 and 1972. Wastes disposed at the facility include irradiated lithium-aluminum targets, oil, and mercury from pumps used in the tritium facility. After 1965, transuranic wastes at the Radioactive Waste Burial Grounds were buried in retrievable concrete containers rather than plastic bags or cardboard boxes. Beginning in 1974, TRU wastes were stored in plastic-lined steel drums. These drums were covered with soil until 1985.
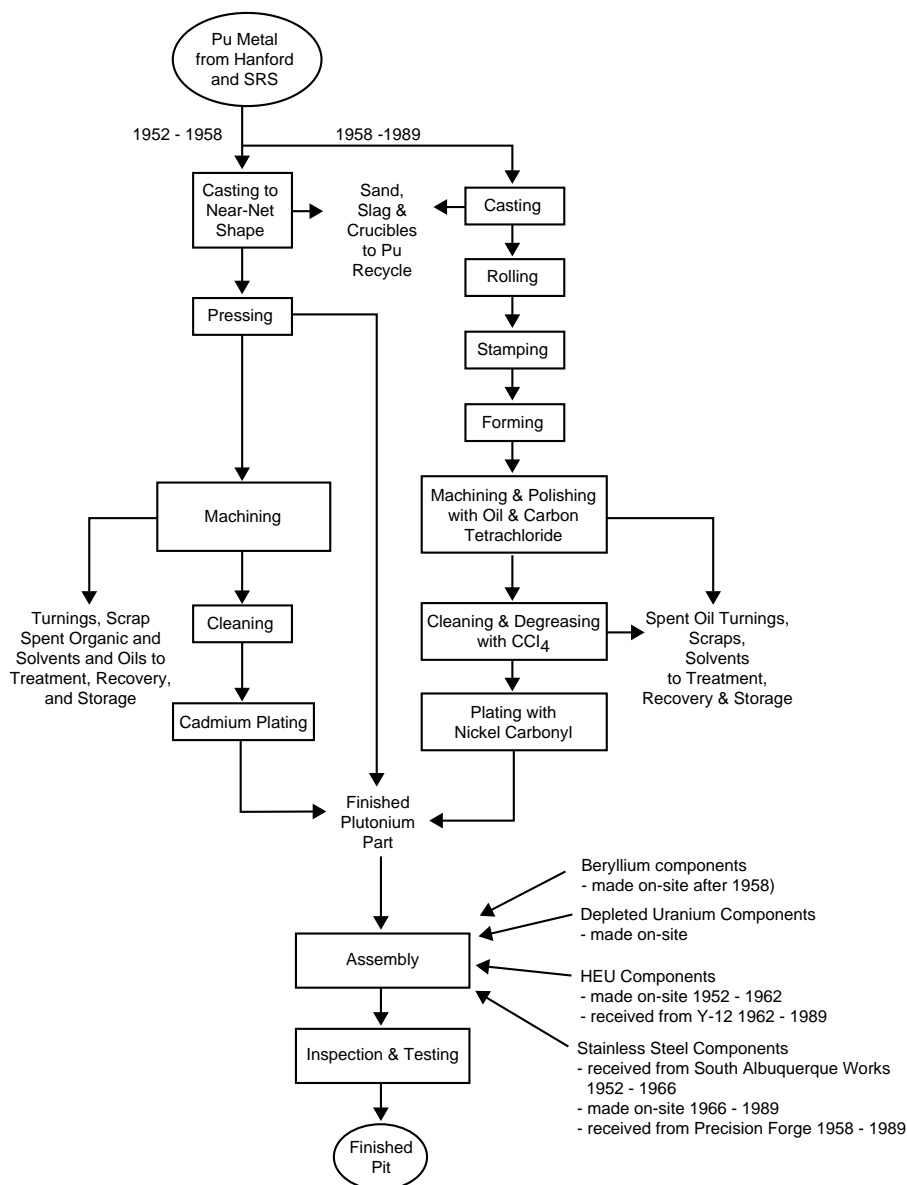
A burial ground also operated in the TNX Area in 1953. Workers excavated most of this waste in 1980 and 1984 and transferred it to the main burial grounds. A new SRS burial ground, the Mixed Waste Management Facility, received mixed wastes from 1969 until November 1988.

Idaho Chemical Processing Plant (ICPP) – To conserve storage space, the Idaho Chemical Processing Plant solidified its high-level wastes into a dry, granular powder. This "calcining" process began in 1963, after 8 years of development. A new waste calcining facility began operating at ICPP in 1982. Calcined high-level waste is stored in stainless steel bins inside concrete silos. Low-level liquid wastes, including those produced by the calcining plants, were discharged to the ground. Sodium-bearing wastes, which could not be calcined, and some other liquid HLW, are stored as acidic liquids in stainless steel underground tanks. Idaho Chemical Processing Plant disposed liquid radioactive wastes using percolation ponds and injection wells.

Solid low-level wastes from Idaho Chemical Processing Plant are buried at the Idaho National Engineering Laboratory Radioactive Waste Management Complex (RWMC). Transuranic wastes were also buried at the RWMC until 1972, when they began to be stored aboveground. While most of these wastes are from component fabrication at the Rocky Flats Plant, a small amount is from the Idaho Chemical Processing Plant. Idaho National EngineeringLaboratory's Waste Experimental Reduction Facility (WERF) reduces the volume of solid wastes by incineration or compaction.

FABRICATION OF NUCLEAR AND NONNUCLEAR WEAPONS COMPONENTS

Figure B-14. Rocky Flats Plutonium Component Manufacturing

Pu Metal from Hanford and SRS

1952 - 1958   1958 -1989

Casting to Near-Net Shape → Sand, Slag & Crucibles to Pu Recycle ← Casting

Pressing

Casting → Rolling → Stamping → Forming

Machining

Machining & Polishing with Oil & Carbon Tetrachloride

Turnings, Scrap Spent Organic and Solvents and Oils to Treatment, Recovery, and Storage

Cleaning

Cleaning & Degreasing with CCl_4 → Spent Oil Turnings, Scraps, Solvents to Treatment, Recovery & Storage

Cadmium Plating

Plating with Nickel Carbonyl

Finished Plutonium Part

Beryllium components
- made on-site after 1958)

Depleted Uranium Components
- made on-site

Assembly

HEU Components
- made on-site 1952 - 1962
- received from Y-12 1962 - 1989

Inspection & Testing

Stainless Steel Components
- received from South Albuquerque Works 1952 - 1966
- made on-site 1966 - 1989
- received from Precision Forge 1958 - 1989

Finished Pit

Weapons *component fabrication* includes the manufacturing, assembly, inspection, local testing, and verification of specialized parts and major weapon components. Chemical processing to recover, purify, and recycle plutonium, tritium, and lithium from retired warheads, and from component production scrap and residues, are included in this category, as are maintenance, recharging, and dismantlement of individual components.

Nuclear weapons components can generally be categorized as either nuclear or nonnuclear. They range from small parts to separately functioning subsystems of weapons.   Nuclear components are located in the primary stage of the weapon, the secondary stage, and in other systems designed to boost nuclear

Rocky Flats glovebox. The Rocky Flats Plant was closed permanently with the end of the Cold War and renamed "Rocky Flats Environmental Technology Site" to reflect its new mission of nuclear materials stabilization, waste management, and environmental restoration. *Rocky Flats Site, Colorado. July 17, 1983.*

performance. Nuclear components in the primary stage are located in the "pit." The nuclear components contain plutonium, highly enriched and/or depleted uranium, lithium-6, deuterium, tritium, and various other, structural parts. Nuclear components have always been manufactured in specialized facilities. Figure B-14 provides a generalized description of the process of manufacturing a nuclear weapon "pit."

Nonnuclear components include arming, fuzing and firing sets, radars, aerodynamic (outer) casings, high-explosive charges, detonators, boost gas transfer systems, batteries, and neutron generators. Although describing all of the processes used to make this wide variety of parts is beyond the scope of this report, Figure B-16 illustrates the general processes for producing electronic components. High explosive component manufacturing is shown in Figure B-17.

Weapons component fabrication also includes the processing of scrap materials to recover and recycle plutonium, uranium, and other materials. Figures B-15 and B-18 illustrate the scrap recovery processes.

Nuclear Component Fabrication

Manhattan Project through the late 1940s – The nuclear components of the three Manhattan Project devices (Fat Man, Little Boy and the Trinity device), the Operation Crossroads test series devices, and the early weapons stockpile were manufactured at the Los Alamos laboratory. Initially, the main chemistry and metallurgy research laboratory in "D Building" was used for this purpose, but the work soon shifted to the new "DP Site" (also known as TA-21), completed in November 1945. Los Alamos received plutonium nitrate paste from the Hanford site, with a small amount coming from the X-10 pilot plant at Oak Ridge, and highly enriched uranium tetrafluoride from the Oak Ridge Y-12 Plant. Nuclear components continued to be manufactured at Los Alamos' DP Site until the start-up of the Plutonium Finishing Plant (PFP) at Hanford in July 1949, and the beginning of HEU casting and machining at Y-12 in 1948.

Figure B-15. Rocky Flats Plutonium Recovery and Purification
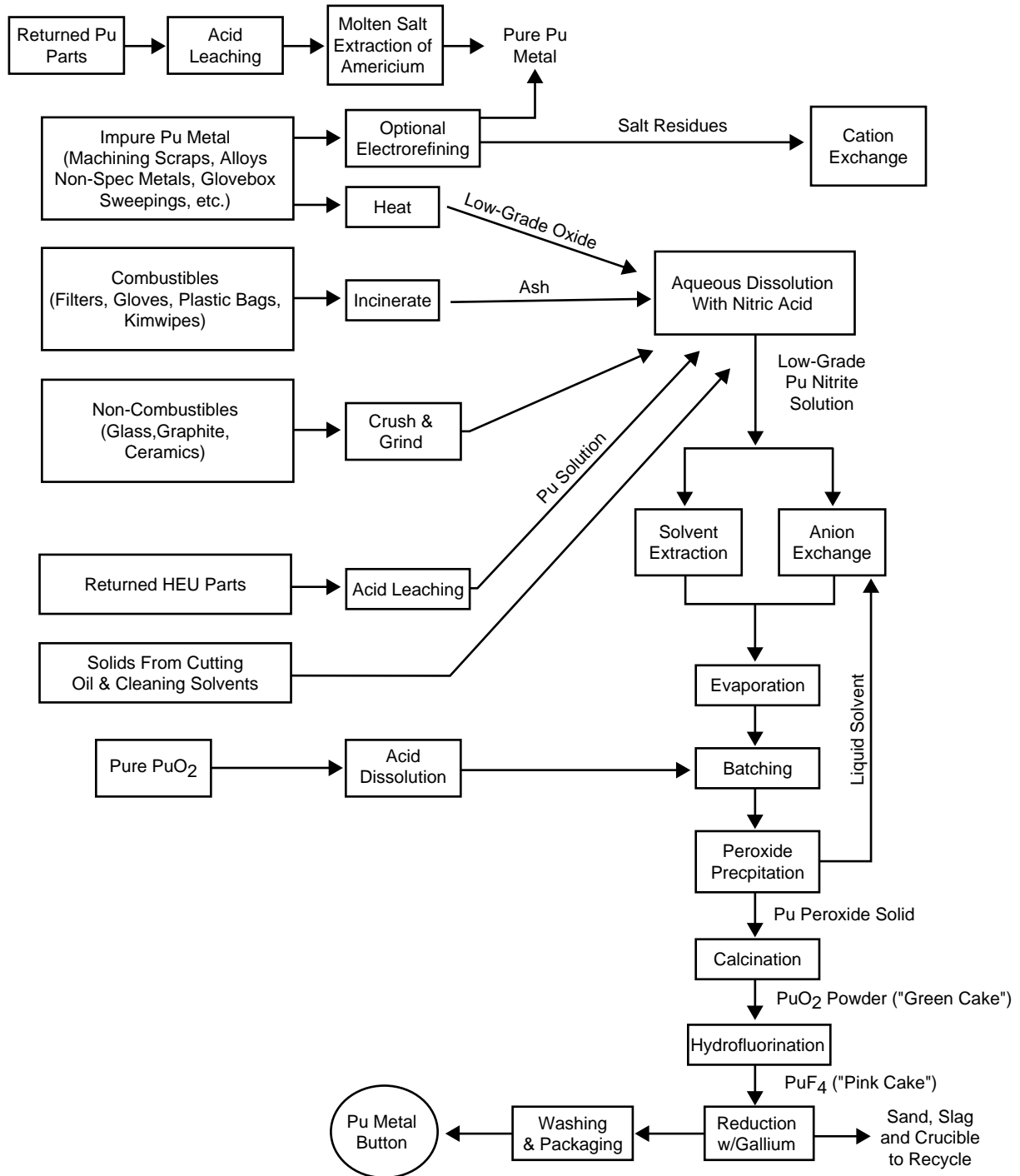
Los Alamos – DP-Site at Los Alamos (also known as TA-21), and its successor, TA-55, fashioned plutonium weapon parts. DP Site was built in 1945 as a production plant for plutonium bomb cores and polonium-beryllium initiators. However, within three years, AEC decided to shift production off site, keeping Los Alamos as a research, development, and design laboratory. DP Site also handled tritium. TA-55 began operations in 1978. After this time, DP-Site nuclear operations were gradually phased out. TA-55 can perform a wide variety of small-scale component fabrication operations, including all of the operations which were conducted at Rocky Flats on a larger scale. For many years, TA-55 had the mission of backup facility to Rocky Flat. However, at Los Alamos, these operations currently are considered part of the RD&T process to support testing. DOE recently announced plans to re-establish Los Alamos as its pit fabrication site.

Oak Ridge Y-12 Plant – Component manufacturing at Y-12 began in 1948 with the casting and machining of HEU weapon parts. Y-12 also processes uranium-bearing scrap and residues, functioning as a central scrap management office for uranium. (See Figure B-18 for a diagram of the scrap management process at Y-12.) Lithium deuteride (Li^{6}D) weapon components have been made at Y-12 since the fall of 1953. The Plant's capability was greatly expanded in the 1950s to encompass the fabrication and assembly of weapons components of depleted natural and highly enriched uranium, beryllium, lithium deuteride, and other materials. From 1968 to 1990, Y-12 received recovered highly-enriched UO$_3$ powder from ICPP and HEU nitrate from Savannah River H Area which was reduced to metal and either stockpiled or used as fuel for its production reactors.

Y-12 also has the mission of dismantling Li^{6}D and HEU components from retired warheads and recycling Li^{6}D. The plant continues to receive and process the secondary components of the nuclear weapons now being dismantled at the Pantex Plant.

Plutonium Finishing Plant (PFP) – The Plutonium Finishing Plant at Hanford (the 234-5 Z Building) began manufacturing plutonium weapons components in July 1949. PFP was equipped with a series of en-closed gloveboxes rather than the open "hoods" previously used at DP Site at Los Alamos. The initial metal reduction and pit fabrication line at the plant (called the "RG line, for "rubber glove") was supple-mented with a remotely-operated line (RMA) in March of 1952, which was itself expanded in early 1953. A second remote line, RMC, that was installed beginning in April 1957 and started production in early 1960. RMA and RMC lines were shut down in December 1965, when Rocky Flats became the sole source of plutonium nuclear weapons parts. RMA was reconfigured to support civilian plutonium fuel develop-ment, while RMC continued to supply plutonium metal to the Rocky Flats plant. The pit fabrication equipment at The Plutonium Finishing Plant was removed and buried in between 1975 and 1976.

Rocky Flats Plant – Rocky Flats, near Boulder, Colorado, was established as a second plutonium and HEU component manufacturing center. Rocky Flats' chief mission was to produce "pits," which are the core components in the first stages of nuclear weapons, known as "primaries." Plutonium used in the pit manufacturing process came from Hanford and the Savannah River Site. HEU came from AEC's gaseous diffusion plants through Y-12. Scrap and residue recovery and returned pits were also a major source of plutonium and uranium feed.

Rocky Flats was initially divided into four areas: the A Plant, today's Building 444, which made depleted uranium parts; the B Plant, now Building 881, which made enriched uranium parts and recovered en-riched uranium from scraps and residues; the C Plant, now Building 771, where plutonium parts were made and plutonium scrap was processed; and the D Plant, now Building 991, where the parts were assembled with others manufactured off site to produce the finished weapon component. Rocky Flats' plutonium processing lines were built as a duplicate of the pit production facilities at Hanford.

In 1962, Rocky Flats ceased producing enriched uranium parts in Building 881. RFP continued to receive HEU pit components from Y-12 for assembly and shipment to Pantex and Burlington. When stainless steel component manufacture (known as the J Line) transferred from the South Albuquerque Works to Rocky Flats in 1966, it was set up in Building 881. When Hanford ceased producing plutonium parts in 1965, Rocky Flats became the sole producer. Buildings 776 and 777 were built to handle the increased

workload, and the mission of Building 771 shifted to plutonium recovery. A major fire in 1969 caused plutonium foundry and machining to be moved from Building 776 to Building 707. Stainless steel component manu-facturing and some nonnuclear metalworking tasks were moved to from Buildings 881 and 444 to Building 460 in 1984.

Initially, plutonium and enriched uranium components from the Hanford PFP and Oak Ridge Y-12 Plants were assembled with locally-made parts in Rocky Flats Building 991. At the time, de-pleted uranium parts were shipped directly to Pantex to be assembled with the completed "pit." In 1957, a significant change nuclear weapon design greatly reduced the need for depleted uranium parts. Beryl-lium component manufacturing replaced the depleted uranium component manufacturing in Building 444. These beryllium components were assembled with the fissile components at Rocky Flats rather than at Pantex. The assembly work shifted to the new Building 777. Building 707 was built in 1969, and took over the assembly mission from the fire-damaged portions of 777.

The Rocky Flats Plant was shut down in December 1989 in order to bring it into compliance with environmental regulations. However, the plant's defense mission was cancelled in 1992 due

Drums of plutonium-bearing residues at the Rocky Flats Plant contain too much plutonium to be disposed of as transuranic wastes. The residues must be stabilized so that they can be stored safely until final disposition plans have been formulated and carried out. *Building 776/777, Rocky Flats Plant, Colorado. December 20, 1993.*

to a change in the needs of the nuclear weapon stockpile, and the plant became an environmental man-agement site. Stabilizing and repackaging the plutonium and plutonium-contaminated scrap and resi-dues that remain at the site is the major mission of the Rocky Flats Plant today.

Waste management at Rocky Flats has remained fairly constant over the years. Rocky Flats built building 774 in 1952 to treat aqueous liquid wastes from the Building 771 plutonium processing facility. Precipita-tion removes some radionuclides as a slurry, which is filtered and solidified as transuranic waste. Until 1973, workers discharged the remaining liquids to either the solar ponds or the "B" series of holding ponds (which drain into the Great Western Reservoir), depending on the radioactivity level in the water. An evaporator began treating liquids that had accumulated in the solar ponds around 1965. The evapora-tor released its vapor to the atmosphere. Rocky Flats stored organic liquid wastes, such as plutonium

contaminated machining oils and carbon tetrachloride degreasing solvents, in drums until a satisfactory treatment could be developed. The Plant first buried drums of organic liquids, then stored them outdoors on a pad. Corrosion caused many of these drums to leak, contaminating the pad and the hillside below it. The contents of some drums were burned. The plant began treating organic wastes by filtering and solidifying the liquids for disposal as TRU waste in 1967.

In 1980, Building 374 opened as the new waste treatment facility at Rocky Flats to supplement Building 774 and eliminate the need to use the Solar Ponds altogether. The same process was used in Building 374 as in Building 774, but the equipment was newer and more efficient.

Rocky Flats shipped transuranic wastes, including contaminated debris from the 1957 and 1969 fires, to the Idaho National Engineering Laboratory until 1988. There have been many instances of radioactive solid waste disposal on site at Rocky Flats in trenches, mounds and burning areas. Nonradioactive solid wastes, such as office waste and cafeteria garbage, have been disposed in two landfills on site. The first landfill operated from 1952 until August 1968, and the second from August 1968 until the present. Sewage sludge burial in on site trenches ended in 1969, when Rocky Flats reclassified the sludges as low-level radioactive wastes.

Nonnuclear Components

Manhattan Project – The Naval Gun Factory in Washington, DC made experimental guns used to develop and manufacture the "Little Boy" device. Other mechanical parts for Little Boy were supplied by the Naval Ordnance Plant in Centerline, Michigan, and the Expert Tool & Die Company in Detroit. Detonators were loaded at the South Mesa site in Los Alamos, using parts from Centerline. After the war, detonator production moved to the larger Two-Mile Mesa site at Los Alamos. Detonating switches and firing assemblies, including radar altimeter fuses, were built by Raytheon in Massachusetts. High explosives from the Yorktown, Virginia, Naval Mine Depot, were molded and machined at Los Alamos' S-Site (also known as TA-16). Initiators had been made at the Los Alamos DP Site using polonium purified by the Monsanto Chemical Company in Dayton, Ohio. The Manhattan Project research at Los Alamos was also supported by many contract shops in the Detroit and Los Angeles areas.

The Salt Wells Pilot Plant at the Naval Ordnance Testing Station, in China Lake, California, assumed the manufacture of high explosive main charges from S Site at Los Alamos in 1946. China Lake, known as "Site I", had been the field location of the MED's "Camel Project," managed by the California Institute of Technology during the war. The MED's Salt Wells Pilot Plant was part of the larger U.S. Navy weapons and testing installation at China Lake. Salt Wells produced high-explosive lenses for MED and AEC until 1954.

Nonnuclear components of nuclear weapons were made at a number of military and private sites in the 1940s. The Rock Island Arsenal in Illinois manufactured armored bomb casings from 1947 until 1951. Private companies manufacturing similar items included the Northrup Aircraft Corporation in Hawthorne, California, the Douglas Aircraft company in Santa Monica, California, the A.O. Smith corporation in Milwaukee, Wisconsin, and the American Car & Foundry corporation in Buffalo, New York, Berwick and Milton, Pennsylvania, and Madison, Illinois. The Picatinny Arsenal, in Dover, New Jersey, has assisted in the development and small-scale manufacturing of components since 1948. Picatinny has worked on fuzes, detonators, firing sets, and generators for U.S. Army nuclear weapons, including nuclear artillery shells, demolition charges, and missile warheads. The Picatinny Arsenal disbanded its nuclear munitions group in the early 1950s, but is still involved in some nuclear-weapons-related tasks.

Iowa Army Ordnance Plant – The Iowa Army Ordnance Plant in Burlington, Iowa, was primarily a weapons assembly facility, but Burlington also manufactured high-explosive components for nuclear weapons from 1947 to 1975.

Mound – The Manhattan Engineer District's Dayton Project to investigate the chemistry and metallurgy of polonium began in 1943. The Monsanto Research Corporation initially analyzed polonium at its Scioto

Workers at a plutonium glovebox. At gloveboxes such as these inside Hanford's Plutonium Finishing Plant, workers once chemically separated and purified plutonium to convert it to metal for nuclear weapon pits. Today, the mission has changed from processing plutonium to storing it. Plutonium is considered a "material in inventory" by the Department of Energy. The workers wear protective suits as an added precaution against any leaks that might occur in the ageing glovebox system. *Plutonium Finishing Plant, Hanford Site, Washington. December 16, 1993.*

research laboratory in Dayton, Ohio. The Dayton Project moved to nearby Miamisburg, Ohio, in 1946, although the Scioto facility remained on standby until the mid 1950s. The Dayton Project became the Mound laboratory in 1947.

The Mound Laboratory's first mission was to manufacture polonium-beryllium initiators for atomic weapons. Mound's initiator manufacturing process included the extraction of polonium-210 from irradiated bismuth slugs and the machining of beryllium parts. Besides producing initiators, Mound focused on polonium research and the search for longer-lived substitute isotopes. The plant picked up several new weapon component production missions over its years of operation. Development, production, and surveillance of detonators began in 1956, and explosive timers developed at the laboratory began to be manufactured on site in 1963. Ferroelectric transducers and firing sets—the electronic components that trigger detonation—began to be built at Mound in 1961. Mound gradually stopped producing initiators after the Pinellas Plant began producing accelerator-type neutron generators in 1957.

Mound began tritium work in 1954, developing and producing nuclear weapon components containing the radioactive isotope of hydrogen. Beginning in 1969, Mound retrieved tritium from retired weapon parts to be recycled.

Nonweapons work at Mound included the development and manufacture of radioisotope thermal generators containing polonium beginning in 1954 and plutonium-238 after 1959. Research at Mound included radioactive waste decontamination studies, investigations of the properties of uranium, protactinium-231 and plutonium-239, and separation of stable isotopes of noble gases. Mound built a plant to process thorium ore and sludge to support breeder reactor programs in 1954 but it never operated. The thorium sludge was stored on site in drums until 1965, and then in a silo until it was sold in 1974.

Mound stopped producing weapons components in 1995, although the plant still produces radioisotope thermal generators for remote power applications, including space probes. Nonweapons polonium work at Mound ended in 1972.

Radioactive waste has never been buried on site at Mound. Oak Ridge accepted Mound's low-level radioactive wastes for burial until 1964, after which they began to be shipped to the Maxey Flats, Kentucky commercial burial site. In 1976, these shipments were rerouted to Barnwell, South Carolina, with high-tritium wastes being shipped to the Nevada Test Site. The Nevada Test Site began accepting all Mound Plant wastes in 1980, however, it stopped accepting Mound wastes in April 1990, causing these wastes to accumulate on site as well. After 1970, transuranic wastes were shipped to Nuclear Fuel Services in West Valley, New York. In 1974, Mound began shipping these wastes to the National Reactor Testing Station (now INEL) in Idaho. After the State of Idaho barred further shipments of transuranic waste in 1988, Mound began storing TRU on site.

Workers at Mound burned and buried hazardous and explosive wastes on site, including beryllium, mercury, trichloroethylene, carbon tetrachloride, benzene, alcohol, nickel carbonyl and plating and photographic processing solutions. These activities were primarily carried out at the Area B Landfill between 1948 and 1969. After 1969, Ohio state law required Mound to dispose of these wastes off site. The Area B Landfill was permanently closed and the waste moved to a new, clay-lined landfill in 1977.

Nonradioactive, combustible solvents and solid wastes were burned at an experimental incinerator at Mound between 1971 and February 1974. Mound also developed and occasionally used a cyclone incinerator for nonhazardous, low-level wastes and a glass melter furnace for treatment of mixed wastes.

A waste treatment plant for liquid low-level wastes from polonium production operated in the WD Building beginning in February 1949. A similar facility in the SM Building treated plutonium 238 wastes beginning in 1961. A second plutonium waste treatment plant in the WDA building started up in 1966. Tritiated wastewater has also been a concern at Mound, beginning with the commencement of tritium processing at the plant in 1954. The SW Building, the plant's principal tritium handling facility since the 1960s, was built in 1953 with a dirt floor with drains to allow spills to seep into the soil. In 1965, an effluent removal system began filtering gaseous releases from the SW Building. By the late 1980s, an integrated tritium recovery and purification facility was removing tritium from Mound Plant waste streams.

Kansas City Plant – Kansas City Plant (KCP) was established in 1949 at the Bannister Federal Complex in south Kansas City, Missouri to make nonnuclear weapon parts: electronics, rubber, plastic foams, adhesives, and others. The plant was initially built to assemble Navy aircraft engines during World War II. In 1995, the Kansas City Plant assumed additional production responsibilities that had been the function of the Pinellas Plant.

Pantex Plant – Pantex Plant was established in the Texas panhandle near Amarillo in 1951 to serve primarily as a weapons assembly plant. However, Pantex also manufactures high explosive (HE) weapons components. Figure B-17 illustrates the HE component manufacturing process. Before becoming part of the nuclear weapons complex, Pantex was a conventional munitions plant operated by the U.S. Army Ordnance Corps.

Workers at Pantex have used firing sites for HE quality control and research since 1952. Some of the test firings at Pantex have involved depleted uranium.

Wastes from the production of high explosive components, including HE-contaminated solid wastes, liquids and solvents, have been treated and disposed of on site at Pantex since 1951. Unlined drainage ditches conveyed runoff and effluents to the playas (shallow artificial lakes) around the plant, where the liquids evaporated. Before it reached the playas, HE-contaminated wastewater was routed through settling and filtering equipment, where most of the HE was extracted in a sludge which was burned on

Rocky Flats was established in 1951 to manufacture plutonium, enriched and depleted uranium, and steel nuclear weapons components. After a similar facility at Hanford shut down in 1965, Rocky Flats became the only source of plutonium "pits" for the U.S. nuclear weapons arsenal. *Rocky Flats Plant, Colorado. July 17, 1983.*

The Mound Plant takes its name from a nearby Native American burial mound. Sited on a hill in the center of Miamisburg, Ohio, Mound was built in 1946 to produce the polonium-beryllium initiators used in early atomic weapons. In the 1950s, the facility began to manufacture a variety of nuclear weapon parts, including cable assemblies, explosive detonators, and the electronic firing sets that activated them. Since 1969, Mound has recovered tritium from retired nuclear warheads. *Mound Laboratory, Miamisburg, Ohio. May 22, 1984.*

The Kansas City Plant manufactured nonnuclear componenets for nuclear weapons. Since 1949, its products included arming, fuzing, and firing systems, radars, power supplies, rubber, plastic and foam parts, and outer casings. This plant is now DOE's only facility for manufacturing nonnuclear components for nuclear weapons. *Kansas City Plant, Bannister Federal Complex, Kansas City, Missouri. July 17, 1982.*

The Pinellas Plant made precisely-timed neutron generators used to initiate fission chain reactions in nuclear weapons. Neutron generators superceded polonium-beryllium initiators which had to be replaced frequently because of polonium's short half-life. Pinellas also made specialized batteries, capacitors, and switches for nuclear weapons between 1957 and 1995. *Pinellas Plant, Largo, Florida. October 19, 1986.*

site. In the 1980s, Pantex replaced the ditches, ponds, and sumps with a system of hazardous waste tanks.

Combustible solid wastes and HE scrap were burned on trays or clay pads in two areas at Pantex. The present burning ground has been in use since 1952, and another was used from 1951 to 1954 and 1959 to 1960. Pantex workers built burn trays on the pads in 1988 to reduce soil contamination. Burn cages disposed of HE -contaminated trash between 1959 and 1967. Pantex no longer uses a chemical burn pit, where waste oils and other chemicals were burned from 1954 until 1980. Between 1980 and 1989, these materials were evaporated before the residues were burned. Since 1989, waste chemicals have been commercially disposed off site. Ash from the burning grounds is buried in landfills on site.

Rocky Flats Plant – Besides manufacturing pits, the Rocky Flats Plant also manufactured tritium gas reservoirs from 1966 until 1989.
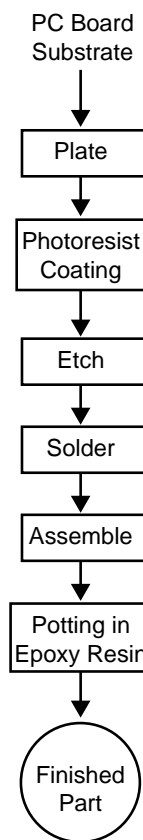
Savannah River Site Tritium Facility – In addition to tritium production, SRS purifies and loads tritium into weapons components. SRS also began purifying tritium recovered by Mound from retired warheads beginning in 1969. The tritium loading function (a component fabrication activity) is a continuing process because tritium decays with a 12.3-year half-life — approximately 5.5 percent decays per year. The original SRS tritium facility, 232-F building began operations in 1955. The 232-F tritium facility was replaced by a facility located in H Area in 1958. A replacement tritium facility at the Savannah River Site H Area began operating in 1994, at which time the 1958 facility was shut down.

Pinellas Plant – The Pinellas Plant was built in Largo, Florida, in 1957 to produce precisely-timed neutron generators to initiate nuclear explosions. The Pinellas Plant's accelerator-type neutron generators gradually replaced the polonium-beryllium initiators manufactured at Mound as the older weapons were removed from the stockpile. Pinellas also manufactured special-purpose capacitors and switches, batteries, power supplies, and other components. DOE shut down Pinellas and transferred all of its functions to The Kansas City Plant at Sandia National Laboratory in 1995.
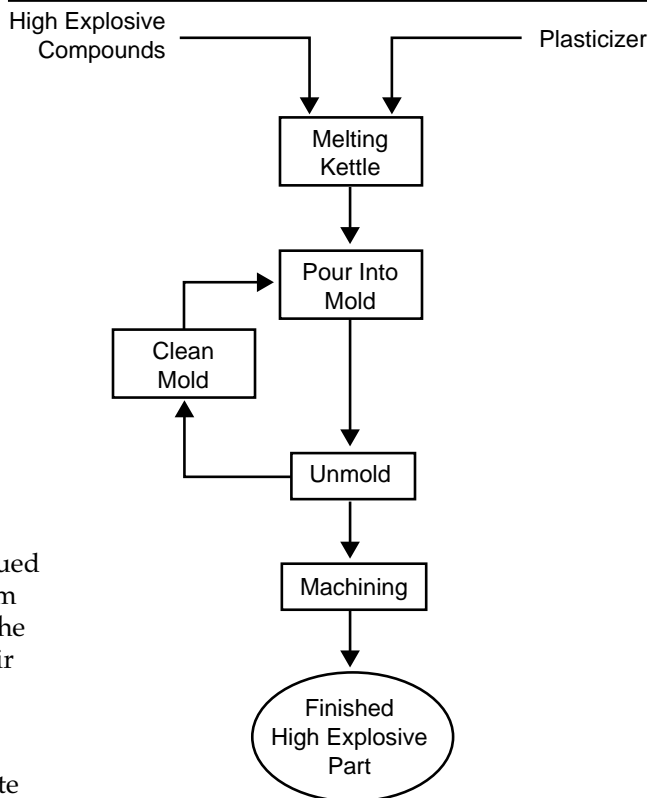
South Albuquerque Works – South Albuquerque Works was established in Albuquerque, New Mexico to manufacture steel weapons parts in 1952. The plant continued to manufacture stainless steel components, including tritium reservoirs, until 1966, when its mission was transferred to the Rocky Flats Plant and the site was transferred to the U.S. Air Force to be used as a jet engine manufacturing plant.

Precision Forge – Precision Forge, established by the Federal Government in Santa Monica, California, in 1958 as a private

Figure B-16. Electronics Fabrication

PC Board Substrate → Plate → Photoresist Coating → Etch → Solder → Assemble → Potting in Epoxy Resin → Finished Part

Figure B-17. High Explosive Manufacturing

High Explosive Compounds, Plasticizer → Melting Kettle → Pour Into Mold → Unmold → Machining → Finished High Explosive Part (Clean Mold loop)

Burn trays are used to incinerate high explosive charges and debris from high explosive packaging on the grounds of the Pantex plant. Modern plastic-bonded high explosives will burn safely without detonating. Pantex was a conventional Army munitions plant before it began assembling nuclear weapons in 1951. *Pantex Plant, Amarillo, Texas. November 18, 1993.*

Hemispheres of high explosives configured like the models in this display are used in an implosion bomb to rapidly squeeze a subcritical mass of plutonium into a denser, supercritical state. High explosive components for nuclear weapons were first made at Los Alamos, than at a pilot plant in China Lake, California, then finally at full scale in Burlington, Iowa, and Amarillo, Texas. *Bradbury Science Museum, Los Alamos, New Mexico. July 15, 1985.*

company, supplied specialized forging for the weapons complex. The company moved to Oxnard, California in 1983, and was purchased by the Department of Energy in 1984 to be managed as part of the Rocky Flats Plant. Precision Forge was privatized again in 1996.

Nuclear Material Recycling

Because of the high cost of obtaining fissile materials and the need for strict accounting and physical security, plutonium and enriched uranium recycling and recovery have been an integral part of the nuclear weapons complex since its beginnings. Scrap and residues containing lithium-6, low enriched uranium, tritium, and other nuclear materials are also processed. These processes address a wide variety of input materials, such as obsolete weapon parts, off-spec alloys, machine turnings, contaminated equipment, used HEPA filters, plastic bags, cleaning solvents and electrorefining salts, yielding pure uranium or plutonium oxide or metal. Batch processes are the general rule. A wide variety of physical and chemical processes are used, depending on the feed material. Figure B-15 illustrates the plutonium recovery processes used at Rocky Flats. Processes used by the Y-12 Plant to recover enriched uranium from returned weapon parts, scrap and process residues are illustrated in Figure B-18.

Rocky Flats – Recovery and purification of scrap plutonium at Rocky Flats began in the spring of 1953 when Building 771 became operational. Recycling and scrap and residue recovery remained an integral part of the plant's operations until it closed. The initial recovery system was a duplicate of the facilities used at Los Alamos at the time. A second "chem line" was installed in 1955. In a major 1965 expansion, another five dissolution lines were added. A new chemical recovery facility, Building 371, was begun in 1973, but it shut down in 1985 without ever achieving full-scale operation. A number of process changes have taken place at Rocky Flats. For example, molten salt extraction replaced an anion exchange process for removing americium ingrowth from recycled plutonium in 1967.

Rocky Flats also recovered and purified uranium scrap and residues in Building 881 between 1952 and 1962. After 1962, uranium parts were produced at the Y-12 Plant and thus no uranium-bearing scrap was available to be processed at Rocky Flats. The uranium recovery equipment at Rocky Flats was removed from Building 881 and disposed of by 1964.

Over time, the small amount of plutonium-241 present in weapons-grade plutonium decays, resulting in a buildup of americium-241. This process is called americium ingrowth. Americium absorbs neutrons during the fission process, making it undesirable for use in nuclear weapon pits. It also presents a gamma radiation hazard which increases over time. As a result, a backlog of americium-bearing residues accumulated at Rocky Flats. Beginning in 1957, americium ingrowth was removed from plutonium processed in Building 771. Until the early 1970s, americium was sold for various commercial uses. However, in 1980, americium recovery ceased and the material has been discarded as a waste since 1986.

Hanford – The Plutonium Finishing Plant (Building 234-5 Z) processed the plutonium scrap and residues from its own defense and nondefense operations.

Savannah River Site F Area – The F Canyon and FB Line facilities process scrap and residues containing plutonium and other actinides.

Y-12 Plant – The Y-12 Plant has long functioned as a central scrap management office for all enriched uranium scrap from DOE sites. The Y-12 Plant also recycles lithium-6 from returned weapon secondaries and recovers and purifies lithium-6 from processing scrap and residues.

Los Alamos – Nuclear materials recycling began at the Los Alamos laboratory in the mid 1940s.   Because plutonium was scarce during the war, great care was taken to recover it from scrap, wastes and residues. Initially accomplished at DP Site, scrap and residue processing was transferred to TA-55 when that facility became available in 1978.

Lawrence Livermore Laboratory – Livermore has a limited plutonium scrap processing capability.

Figure B-18. Enriched Uranium Recovery Process Used at the Y-12 Plant
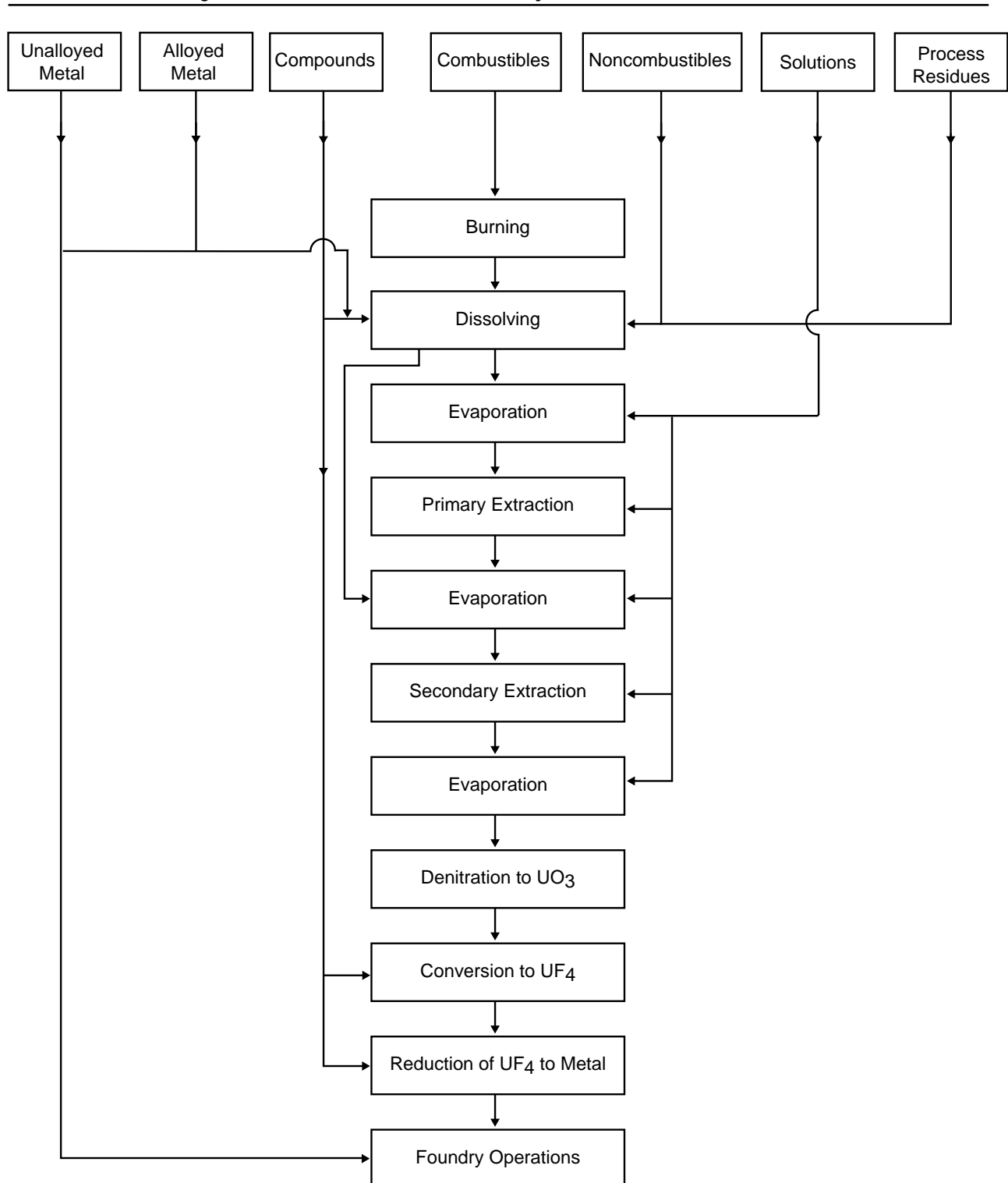
Note: Uranium scrap and residue processing at Y-12 is similar in many ways to plutonium recycling. Feed materials containing enriched uranium are prepared by incinerating combustibles, crushing and dissolving solid residues and scraps, and concentrating uranium solutions. Solvent extraction purifies the uranium, which is solidified to UO$_3$ by denitration, converted to UF$_4$, and reduced to metallic uranium. As with plutonium scrap recovery, Y-12 processes HEU scrap and residues using equipment designed to prevent accidental nuclear criticality.

WEAPONS OPERATIONS
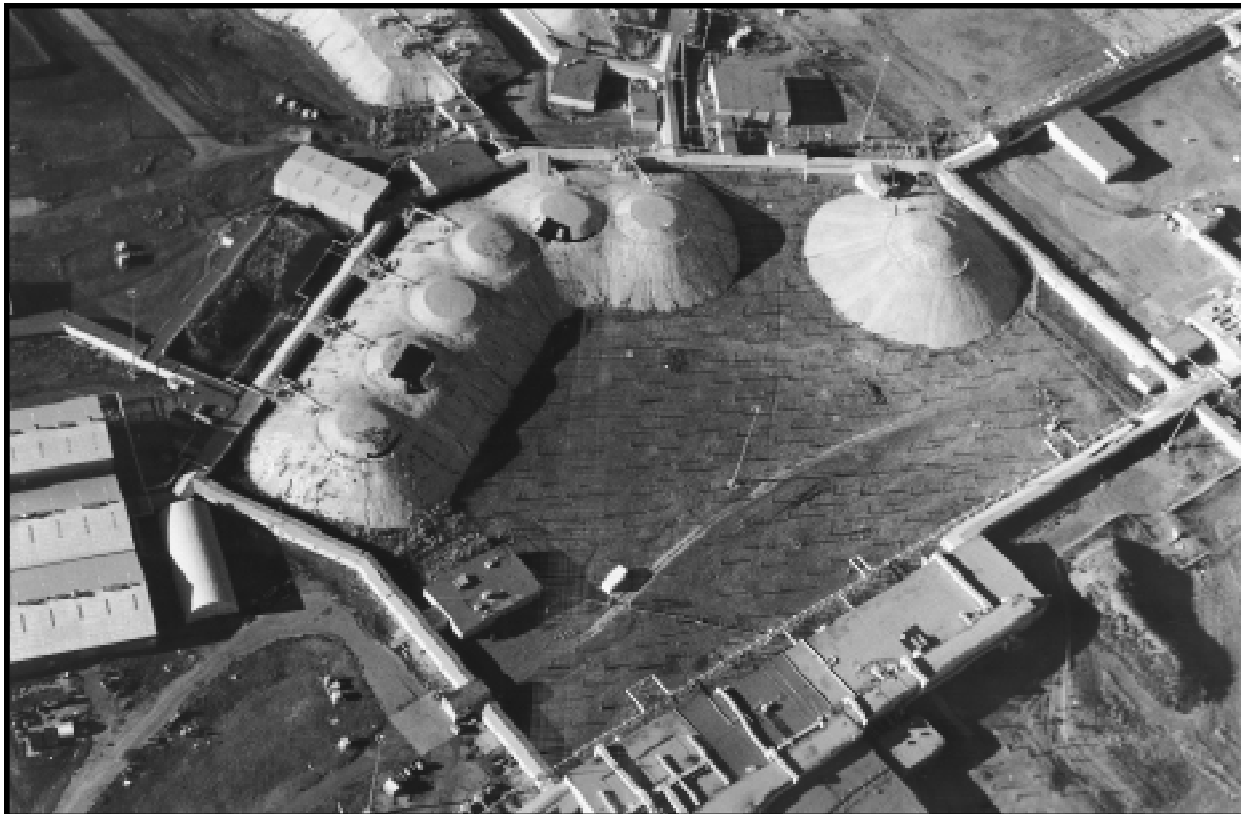
"Gravel Gerties" are circular concrete structures whose roofs consist of cable mesh supporting large amounts of gravel. Beneath them are bays, where workers assemble and disassemble nuclear warheads. Should a warhead's conventional explosives accidentally detonate, the roofs of these structures are engineered to give way, releasing the gravel and trapping the plutonium particles. Up to 2,000 warheads per year are now being dismantled at this site. *Pantex Plant, Amarillo, Texas. November 18, 1993.*

Weapons Operations include assembly, maintenance, modification and dismantlement of nuclear weapons stockpile warheads. Assembly is the final process of joining together separately manufactured components and major parts into complete, functional and certified nuclear weapon warheads for delivery to the Department of Defense (DoD). Dismantlement of retired warheads includes disassembly of weapons and the sanitization, demilitarization and disposition of their component parts. Warhead modifications and maintenance by DOE are also included in this category, although field maintenance by DoD is not.

Only small amounts of radioactive wastes were produced by weapon operations, because most of the radioactive materials in nuclear weapons are handled only as sealed parts. However, weapon operations produced chemical wastes as a result of cleaning, painting, assembly and disassembly activities.

The first test devices and warheads were partially assembled by Manhattan Project scientists on the Pajarito Plateau at the Los Alamos S-Site, or TA-16. The scientists completed the assembly of the Trinity test device at the McDonald ranch house and atop the tower at the Alamogordo, New Mexico test site.

Final assembly of test devices has always been performed at the test site. This activity has been considered in this report as part of the legacy of research, development and testing and at other nuclear testing sites in the Pacific.

To maintain civilian control as required by the Atomic Energy Act, the nuclear cores and initiators of early nuclear weapons were stored separately from the remainder of the weapon. The cores were to be inserted

just before the weapon was used, a procedure known as "in-flight insertion." Pre-assembled bombs—without cores or initiators—were stored in bunkers at military bases. Employees of the Sandia division of Los Alamos Scientific Laboratory and, after it was formed in 1949, Sandia Laboratory, had custody of the nuclear components in adjacent storage bunkers. Maintenance and modification of the U.S. nuclear weapons stockpile was also done at these bases, at the direction of the AEC design laboratories.

Advances in nuclear weapons technology in the 1950s allowed for major changes in these arrangements. Most significantly, weapon designers developed coded locks, called permissive action links, that prevent the arming of a nuclear weapon without the proper code. These devices allowed civilian authorities to maintain control over the nuclear arsenal while completely relinquishing physical custody of the weapon. They also reduced the time necessary to deploy nuclear weapons in case of attack. By 1962, AEC had discontinued its custodial role at military nuclear weapons stockpile bases.

In July 1945, MED acquired part of Oxnard Field (now Kirtland Air Force Base) in Albuquerque and converted it into a weapons assembly site. The site was then known as Sandia Base and was manned by personnel from Los Alamos. The site was reorganized into a separate laboratory in 1949. Weapon assembly functions were performed at Sandia Base beginning in 1945. In 1948, Sandia built a production and assembly line in Technical Area 2 that operated until 1957.

To supplement Sandia's nuclear weapons assembly capacity, AEC built two assembly plants. The Iowa Army Ordnance Plant was built in Burlington, Iowa, in 1947 for final assembly. AEC selected the Pantex Ordnance Plant near Amarillo, Texas in 1950 as its second nuclear weapons assembly facility. Pantex began assembling nuclear weapons in 1951. Between 1942 and 1945, Pantex had been a conventional munitions factory, loading high explosives into bombs and artillery shells. Although the Army initially retained administrative control, Pantex was completely transferred to AEC in 1963. AEC changed the name of the facility to the Pantex Plant.
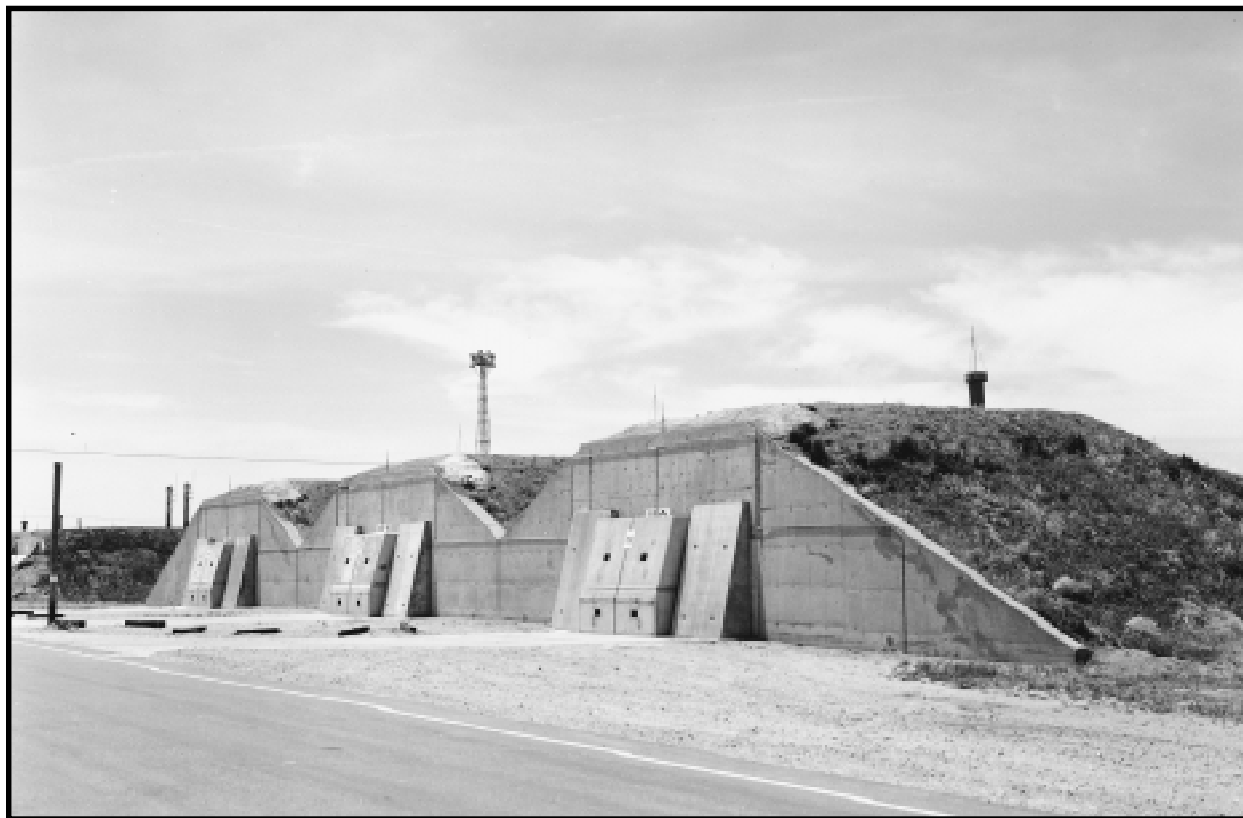
Staging bunkers, or "igloos," contain nuclear weapons and plutonium pits from dismantled warheads. There are 60 of these earth-mounded bunkers in a high security zone of the Pantex Plant. Sixteen of them store plutonium pits; the remaining 44 house nuclear weapons entering or exiting the plant. *Pantex Plant, Amarillo, Texas. May 23, 1986.*

The Burlington plant operated until 1975 when its functions were transferred to Pantex, which remains the Department of Energy's sole facility for weapon assembly, modification and dismantlement to the present day. DOE built an assembly plant, called the Combined Device Assembly Facility, at the Nevada Test Site in the 1990s, but it has not been used.

Modification of nuclear weapons by the military at its many stockpile storage sites eventually proved too cumbersome to be continued. In the 1950s, AEC began modifying and upgrading nuclear weapons at its assembly plants.

AEC constructed two supporting plants in 1958, the Clarksville Modification Center on the Ft. Campbell Military Reservation in Clarksville, Tennessee, and the Medina Modification Center in Medina, Texas. These sites performed specific tasks that were part of the assembly, dismantlement, and maintenance process, such as weapon repair and modification and component modification and testing. As part of scale-back instituted by President Johnson, the Clarksville and Medina facilities were closed in 1965 and 1966, respectively, and their functions transferred to Burlington and Pantex.

The major mission at Pantex today is dismantlement of nuclear weapons. Once a weapon is dismantled, Pantex sanitizes and demilitarizes many of the nonnuclear components, including electronics, cables, structural parts, parachutes and explosive actuators. *Sanitization* is the removal of classified information from weapon parts; *demilitarization* is the removal of their military function. Pits from dismantled weapons are stored on site, while secondaries, which produce thermonuclear reactions, are returned to the Y-12 Plant in Oak Ridge, Tennessee. Components containing tritium are sent to the Savannah River Site where the tritium is recovered and purified for reuse. The Mound Plant recovered tritium from some components from 1969 until the plant was shut down in 1995.

RESEARCH, DEVELOPMENT, AND TESTING

Los Alamos National Laboratory. Located on top of a mesa in the Sangre de Christo mountains of New Mexico, the Los Alamos National Laboratory was the birthplace of the world's first atomic weapons. It continues to function today as one of America's two main nuclear weapons design laboratories. *Los Alamos, New Mexico. June 15, 1983.*

Weapons *Research and Development* (R&D) is conducted by DOE national weapon laboratories and test sites whose primary mission is to support the nuclear weapons program.   This includes basic and applied research with weapon applications and the design and testing of nuclear weapons systems. Weapons-related research has also been conducted by most of the DOE's multi-program laboratories.

Localized R&D to support specific site missions (such as fuel fabrication) is generally considered part of each local site mission, except in specific cases where the legacy generated is clearly distinguishable as resulting from R&D, and the R&D enables the site to better perform its overall mission in support of the national weapons program. Department of Defense laboratories and their activities are not discussed in this report. Research and development activities have produced a broad assortment of wastes, contamination, and large volumes of contaminated soil and debris.

Testing includes the preparation and instrumentation of the test site and device, the placement and detonation of the device, and the post-detonation analysis and cleanup. It also includes nonnuclear tests of weapon ballistics and other aspects of the military utilization of nuclear weapons. Tests which produced only small nuclear yields ("safety experiments") which intentionally did not produce a nuclear explosive yield, are also included in this category. Nuclear testing has resulted in large areas of contaminated soil and other environmental media, some areas being highly contaminated.

Early Research and Development

Much of the early theoretical and experimental work that led to development of the first nuclear weapon was accomplished outside the United States. For example, Rutherford's artificial transmutation of nitrogen into oxygen in 1919 (England); Chadwick's discovery of the neutron in 1932 (England); Fermi's early work with neutron bombardment in 1934 (Italy), and Hahn and Strassmann's discovery of the process of fission in uranium (Germany).

In the United States, nuclear physics research was being done at many institutions, including the University of California at Berkeley, Columbia University, Princeton University, the University of Minnesota, the University of Wisconsin, Stanford University, Purdue University, Iowa State College, Cornell University, the Rice Institute, the University of Chicago, the Massachusetts Institute of Technology, the University of Rochester, Harvard University, the University of Illinois, and the Carnegie Institute of Washington and the National Bureau of Standards. American researchers made a number of fundamental contributions, such as Ernest Lawrence's operation of the world's first particle accelerator, the cyclotron, in 1932 and later development of electromagnetic isotope separation; Bohr and Wheeler's 1939 work on fission theory at Princeton; Zinn, Anderson, Fermi and Szilard's, chain reaction and pile experiments at Columbia University in 1939-40; Dunning and Nier's work on uranium-235 fission at Columbia and Minnesota; and the 1941 discovery of plutonium by Seaborg and his colleagues at Berkeley.

By mid-1942, government support resulted in research being concentrated at Columbia University (gaseous diffusion and gas centrifuge for uranium separations), Berkeley (electromagnetic process for uranium separations), and University of Chicago Metallurgical Laboratory (chain reacting pile to produce plutonium). The thermal diffusion process for uranium separation had been dropped from consideration to produce material for a weapon but retained by the Navy for propulsion research. Many commercial organizations were involved in Manhattan Project research. Some of the larger contributors were E.I. du Pont de Nemours, Monsanto Chemical Company, Westinghouse Electric Company, and the Mallinckrodt Chemical Works.

Construction of a centralized laboratory for atomic bomb research and production began at Los Alamos, New Mexico (called "Site Y"), in November, 1942. In March, 1943, scientists and technicians began arriving at the laboratory. Early organization featured theory, experimental physics, chemistry and metallurgy, ordnance groups and many shops. The laboratory's mission was to develop and apply chain reaction and fissile material assembly theory, measure the physical, chemical, and nuclear parameters of various materials, develop processes for chemically purifying and fashioning uranium and plutonium, and engineer the final bombs. Initially, research concentrated on the "gun assembly" device, which assembled two subcritical masses into a supercritical mass using a gunbarrel. After it was discovered that this method would not work with plutonium because of its high neutron background, development of the plutonium bomb concentrated on implosion. Implosion uses explosives to compress a subcritical mass into a supercritical mass.

Los Alamos was assisted in its task by many other laboratories. The University of Michigan developed radar fuses and ordnance research. Scientists at the Dahlgren Naval Proving Ground, in Virginia, also performed ordnance research and development for the Manhattan Project. Explosives and gun propellant research at the Explosives Research Laboratory in Bruceton, Pennsylvania was crucial to the development of the atomic bomb. The Naval Gun Factory in Washington, D.C. made test guns for the development of the gun assembly device. Monsanto developed purification techniques for the polonium used in the initiators. Ohio State University researched the properties and manufacture of liquid deuterium. Plutonium chemistry and metallurgy were researched at U.C. Berkeley and the University of Chicago. Crucibles for reducing plutonium to metal without introducing light-element impurities were developed and manufactured by MIT, Iowa State College and Brown University. Experimental detonators came from the Hercules Powder Company. The "Camel" project, managed by the California Institute of Technology (CalTech) began in late 1944 to study weapon assembly mechanisms and combat delivery and to research and engineer specialized components including detonators.

The Tower Shielding Reactor. These towers were built to allow prototype aircraft propulsion reactors to be raised several hundred feet in the air for experiments. A small reactor at the base of the towers provided radiation to measure the shielding properties of materials for weapons and nonweapons programs. *Tower Shielding Reactor, Oak Ridge National Laboratory, Tennessee. June 10, 1982.*

The N Tunnel. Nuclear weapons effects tests were conducted in horizontal tunnels dug into the side of Ranier Mesa at the north end of the Nevada Test Site. DOE often cooperated with the Department of Defense to test the effects of nuclear weapons' radiation on military hardware, such as satellites and missile warheads. Workers here prepare for a test code-named "Misty Rain." On April 6, 1985, a nuclear device was detonated in a "zero room" 875 feet from this chamber. Air had been pumped from the pipe and chamber to simulate the vacuum of outer space. Radiation from the explosion traveled down the pipe to the test chamber at the speed of light, while blast doors blocked the explosion's shock wave. *N Tunnel, Area 12, Nevada Test Site. October 29, 1984.*

Signal cables laid out on the desert floor at Yucca Flat. These cables relayed scientific data to recording trailers on the surface as the nuclear device detonated deep underground. The tower above the emplacement hole was used to assemble a package of scientific instruments in a canister attached to the nuclear device. The tower was dismantled before the detonation took place. *Yucca Flat, Nevada Test Site. (No date available.)*

Supercomputers like these at Lawrence Livermore National Laboratory are used to analyze and simulate nuclear explosions. *Lawrence Livermore National Laboratory, California. June 13, 1984.*

Post-World War II Research and Development

After the initial surge of research work at universities and private laboratories in support of the Manhattan Project, nuclear weapons R&D work concentrated in a small number of government facilities. Some research continued outside these laboratories, for example, deuterium research at Ohio State University.

After World War II, the MED installation at Los Alamos, New Mexico became the Los Alamos Scientific Laboratory (LASL). In 1982, DOE directed the national laboratories to incorporate the word "national" in their official names, and LASL became Los Alamos National Laboratory. It is primarily a weapons design laboratory, although its nonweapons work load has grown considerably.

On occasion, Los Alamos has also performed weapons or materials production tasks. For example, in the 1980s, it built selected pits at TA-55 to exercise its mission to provide a back-up for RFP and reduced Hanford PuO$_2$ to plutonium metal for a short period after an accident at Hanford. However, the primary mission of Los Alamos has always been R&D for the specific purpose of theoretical design of the nuclear components of nuclear weapons and the radioactive legacy, therefore, has been weapons R&D related. A branch of the LANL testing division is also located at the Nevada Test Site.

On November 1, 1949, Sandia Laboratory was formed at Sandia Base on the grounds of Oxnard Field (now Kirtland Air Force Base) near Albuquerque, New Mexico. The new laboratory was formed from the Los Alamos Laboratory's Ordnance Engineering "Z Division," which had operated the site since July 1945 as a nuclear device and weapons assembly point and engineering design organization. The mission of the new laboratory was weapons RD&T, specifically the design of nonnuclear components of nuclear weapons. The location of the original laboratory was chosen to continue direct support to Los Alamos. A branch of SNL is also located at the Nevada Test Site. In 1982, the Sandia Laboratories were renamed the Sandia National Laboratories (SNL) by DOE directive.

In February 1952, Livermore, California was selected as the site for a second, dual capability, nuclear weapons design and R&D laboratory, to focus specifically on the development of thermonuclear weapons. AEC encouraged friendly competition between the two laboratories to stimulate research. The site officially opened in September 1952 as the University of California Radiation Laboratory-Livermore. The laboratory's name changed to Lawrence Livermore Laboratory (LLL) in 1971, and again to Lawrence Livermore National Laboratory (LLNL) in 1982 by DOE directive. It has occasionally performed minor production-related tasks, but its primary mission is weapons RD&T. A branch of Lawrence Livermore is located at the Nevada Test Site. In 1956, a branch of Sandia was formed at Livermore to provide the needed direct support of Lawrence Livermore Laboratory.

Los Alamos, Livermore and Sandia weapons R&D has ranged well beyond theoretical studies and design work. The laboratories have investigated the chemical, physical and metallurgical properties of nuclear materials. Manufacturing techniques to be used at production facilities are developed at the labs. Tests of high explosives have evaluated weapon design features. Simulations of environmental effects on nuclear weapons, including radiation, are also done by the weapons laboratories.

Nuclear Testing Sites

The United States has conducted a total of 1,054 nuclear tests, including 24 joint U.S.-U.K. tests. These tests have been conducted for several purposes. Eight hundred and ninety-one detonations have been weapons related tests to prove that a weapon would function as designed or to advance weapon design. One hundred detonations have been carried out to explore the effects of nuclear weapons on structures, equipment, and other weapons. Eighty-eight safety experiments have been performed to assess the likelihood of an accidental nuclear detonation, along with four storage and transportation related detonations and 24 joint U.S.-U.K. detonations. Seven detonations have been performed to develop means of detecting nuclear explosions from a great distance. Finally, 35 detonations explored non-military uses of nuclear explosives. (Some of the 1,051 tests comprise multiple detonations.)

Alamogordo, New Mexico – The first United States nuclear weapon test, code named "Trinity" by the Manhattan Engineer District, took place on July 16, 1945. The Trinity test site was the Jornada del Muerto region in the northwest corner of the Alamogordo Bombing Range in southern New Mexico. Today, the site is part of the White Sands Missile Range.

Pacific Proving Ground – Bikini Atoll and Enewetak Atoll in the South Pacific were the sites of MED and AEC weapons testing following the end of World War II, beginning with Operation Crossroads at Bikini Atoll in June and July of 1946. After a two-year hiatus, testing in the Pacific resumed in 1948. The primary Pacific test site was the Enewetak Proving Ground, although significant thermonuclear testing was conducted near and on some of the islands of Bikini. The Enewetak Proving Ground was placed on standby after Operation Hardtack I in 1958 and officially abandoned in 1960. Restoration of Enewetak was authorized by Congress in 1978 and performed by the Army Corps of Engineers for the Defense Nuclear Agency between 1978 and 1980. Cleanup was accomplished by entombing contaminated materials, which allowed previous residents to return to the area. The restoration of Bikini Atoll was accomplished by removal of contaminated materials and testing debris in 1969.

Other Offshore Test Sites – The United States conducted nuclear weapons tests in several other offshore locations, including (1) Shot Wigwam, detonated underwater 400 miles southwest of San Diego in 1955; (2) Operation Argus, 3 high altitude test shots in the South Atlantic Ocean in 1958; (3) four shots in the Pacific Ocean, including 2 underwater shots, one submarine-launched missile, and a balloon-suspended device; and (4) at a variety of oceanic locations near Johnston Island and Christmas Island as part of Operation Hardtack I and Operation Dominic, 1958-1962. These locations require no restoration.

Nevada Test Site (NTS) – NTS was established in 1951 and was originally known as the Nevada Proving Grounds. A test site in the continental United States reduced the costs and logistical delays involved in testing at Bikini and Enewetak. The site also allowed the Army to conduct land-based troop maneuvers to simulate atomic warfare. There have been 925 nuclear tests at NTS since 1951. The first nuclear tests (called "shots") at NTS, the Operation Ranger series in 1951, were air-dropped air bursts which produced relatively small patterns of induced contamination on the ground. However, during subsequent tests through Operation Teapot in 1955, there were many tower-mounted test shots and a few surface and subsurface test shots resulting in significant fallout. Operation Plumbob in 1957 featured the first balloon-suspended shots which significantly reduced but did not entirely eliminate surface contamination. Shots Pascal A & B and Rainier, also in 1957, were the first attempts to gather data for underground containment and prepared the way for confining all tests underground by late 1962 before imposition of the Limited Test Ban Treaty in 1963.

Since 1963, all nuclear tests at The Nevada Test Site have been conducted underground. DOE-sponsored weapons development tests have been fired in deep shafts and weapon effects tests, principally a DoD concern, were fired in tunnels. These explosions have left underground cavities filled with a vitrified mixture of soil and explosion residues. Drilling to create test holes and drillback to retrieve post-test samples has resulted in drilling "mud" contaminated with radioactive and hazardous materials.

The Nevada Test Site currently buries low-level waste on site, and it disposed of mixed low-level waste in the same manner until 1990. Some low-level waste buried there was generated on site, but large quantities were also shipped from other locations. Old test craters U3ax and U3ax-b1 in Area 3 primarily contain contaminated debris from cleanup of atmospheric nuclear test areas at Yucca Flats. Area 5 shallow trenches and boreholes have received significant shipments of waste from Rocky Flats , LLNL, Mound, and Fernald. The Nevada Test Site also currently stores mixed TRU waste from LLNL.

Amchitka Island – Three nuclear tests were conducted on Amchitka Island, Alaska: Test "Long Shot" on October 29, 1965, shot "Milrow" on October 2, 1969, and shot "Cannikin" on November 6, 1971. "Long Shot" was for nonweapons purposes (see "Vela Uniform"), but "Cannikin" and "Milrow" were weapons-related tests. The area is now managed as the Amchitka Island Test Site.

Figure B-19. Underground Testing
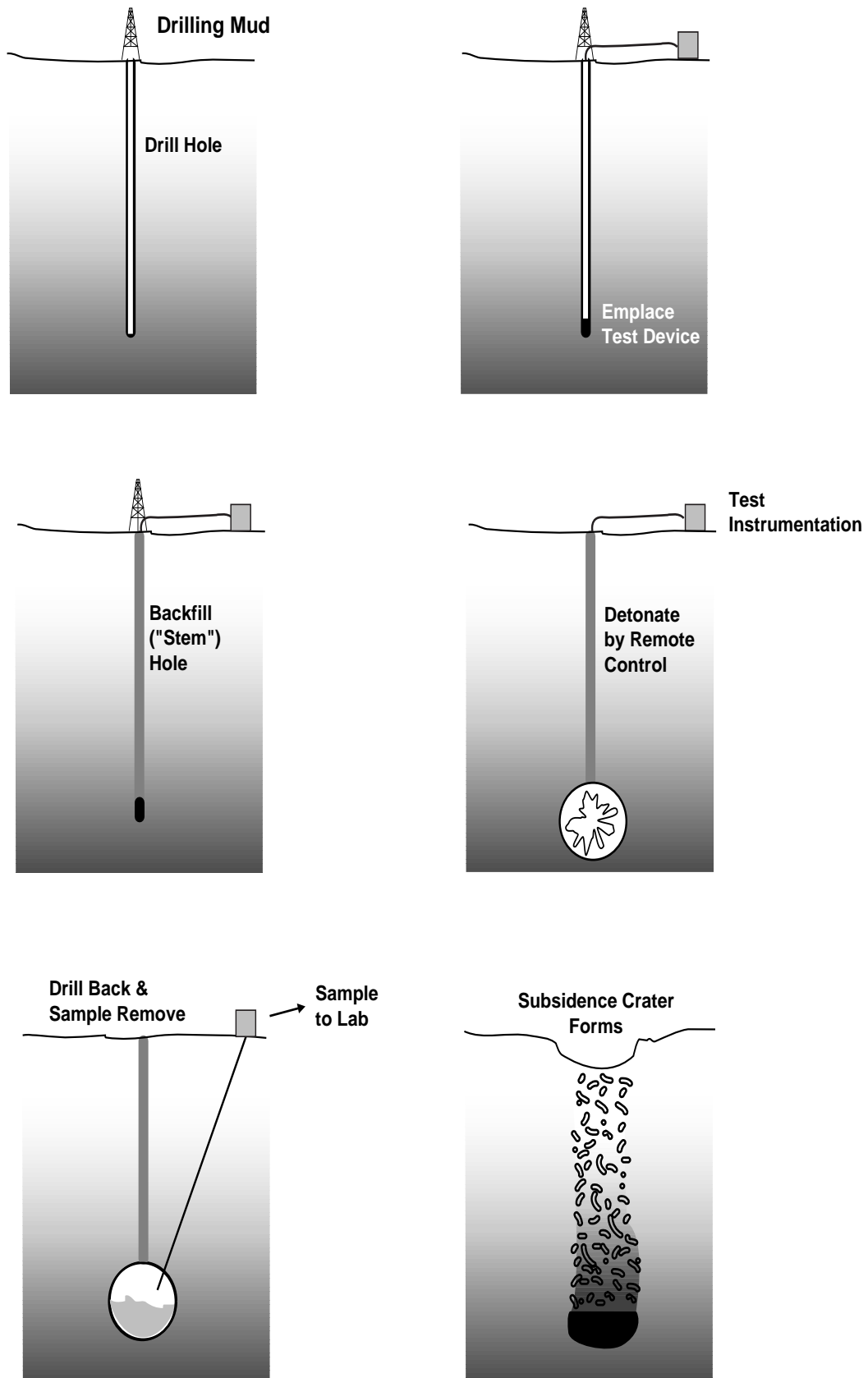
Other Continental Sites – Nuclear Test Faultless, a weapons-related seismic calibration test, was detonated in Central Nevada on January 19, 1968.

The United States government investigated the application of nuclear explosives for peaceful purposes during the 1960s and 70s. This effort was called, "Project Plowshare." Project Plowshare conducted 35 nuclear detonations between 1961 and 1973. Most Plowshare detonations were at the Nevada Test Site, but Plowshare experiments were also conducted at Carlsbad and Farmington, New Mexico; and Grand Valley and Rifle, Colorado.

"Vela Uniform" was a Department of Defense program to improve the United States' ability to detect, identify and locate underground nuclear explosions. The program began in 1963 with the "Shoal" detonation in Fallon, Nevada, and it continued though 1971. A total of seven Vela Uniform tests were conducted, including one test at Amchitka, Alaska; two at Hattiesburg, Mississippi; and three at the Nevada Test Site.

Nonnuclear Testing Sites

Manhattan Project Sites – To develop ballistics information for the atomic bombs, drop tests were done at Wendover Field, Utah. Bomb ballistics drop tests were also made at the Camel Project field site, in China Lake, California, and the Sandy Beach area of the Salton Sea, California, Naval Air Station. Arming and fusing systems were field tested at Muroc Air Base (now known as Edwards Air Force base) in California. Radar altimeter fuses were tested at Warren Grove, New Jersey using barrage balloons.

Salton Sea Test Base – Salton Sea Test Base was used in the 1940s and 1950s as a sea-level ballistics range to obtain performance data on inert nuclear weapons prototypes. It was formerly operated by Sandia, and currently is owned and operated by the U.S. Navy. AEC transferred its Salton Sea Test Base activities to the Tonopah Test Range in 1961.

Tonopah Test Range – The Tonopah Test Range (Nye County, Nevada) was established in 1957 for the testing of nonnuclear systems and components of bombs. Typical examples of items tested there are bomb delivery systems, bomb-delivery retardation chutes, and artillery shell trajectories. Tonopah was operated by Sandia National Laboratory in Albuquerque.

Kauai, Hawaii – Sandia National Laboratory has conducted some nonnuclear weapons testing in Hawaii at the Navy facility on Kauai, now managed as the Kauai Test Facility. Among other missions, Kauai has been used to launch missiles carrying experimental, nonnuclear payloads.